halo formation due to beam-beam

Frank Zimmermann, CERN AB/ABP

measurements
simulations
analytical models

leptons & hadrons

lepton-lepton	lepton-hadron	hadron-hadron
DAΦNE,…		
SPEAR		
VEPP-4		
CESR		**ISR**
PEP-II	**HERA**	**SPS**
KEKB		**Tevatron**
PETRA, PEP,…		**RHIC**
LEP		LHC

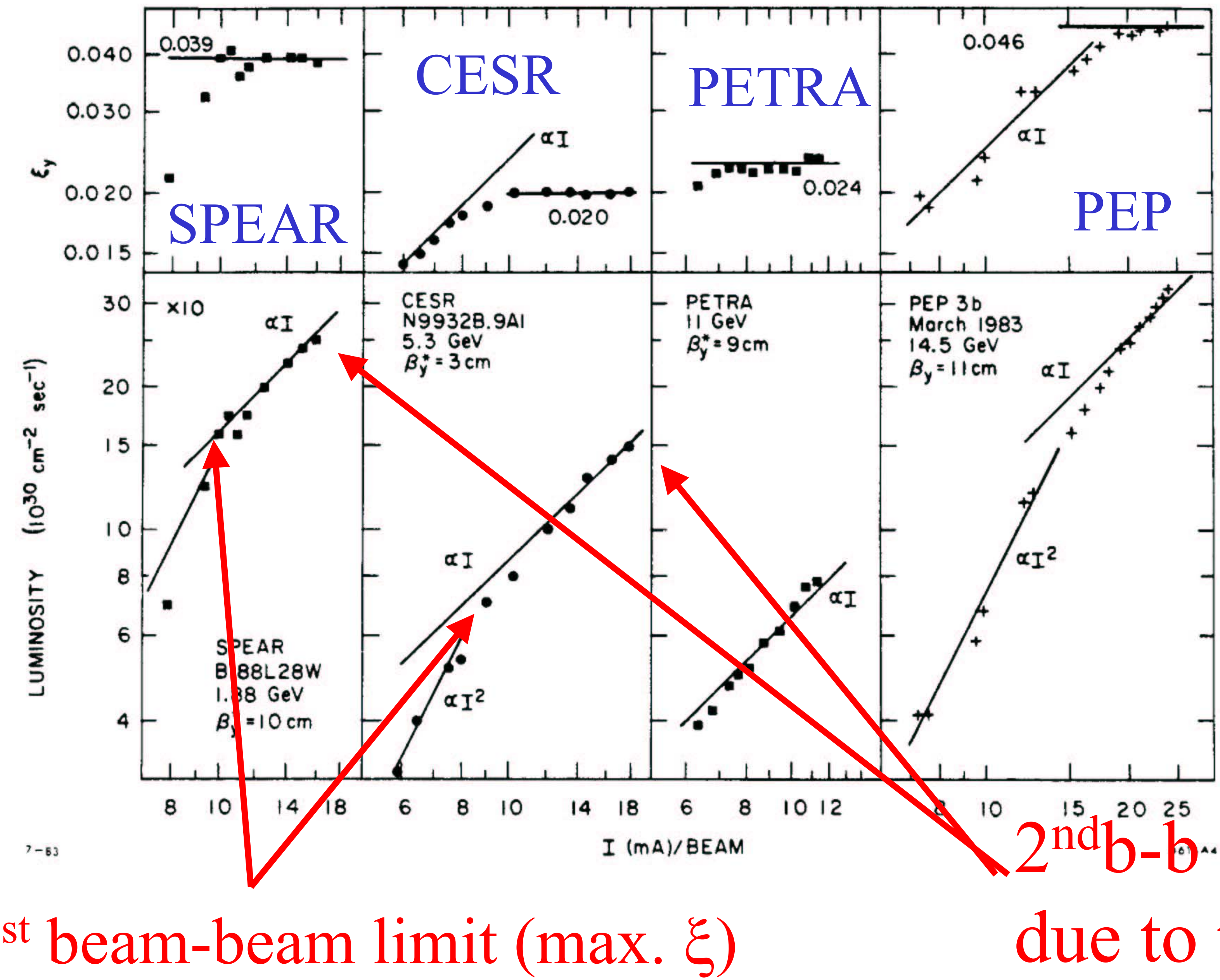
increasing energy,
shorter damping times

	beam energy [GeV]	tune shift per IP	total tune shift	damping decrement per IP
LEP	**100**	0.083	0.33	**1.6×10^{-2}**
KEKB	8, 3.5	0.05-0.095	0.05-0.095	**2×10^{-4}**
DAFNE	**0.51**	0.03	0.03	**10^{-5}**
LHC	**7000**	0.003	0.01	**5×10^{-10}**
Tevatron	980	0.01	0.02	**5×10^{-12}**

tails in lepton colliders

- ‘steady-state’ equilibrium due to radiation damping
- tails cause background & reduce lifetime
- often limit luminosity

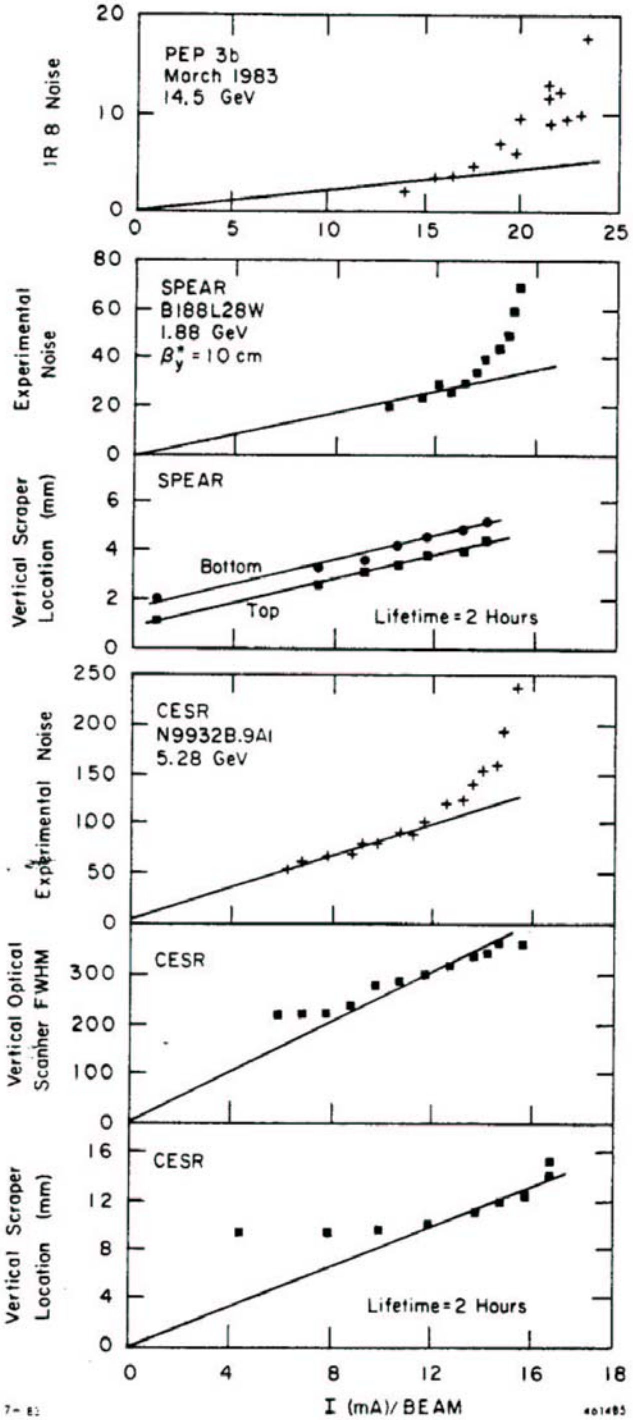
ξ & luminosity vs. current for e⁺e⁻ rings



(See-man, 1983)

PEP

CESR



noise vs. current (sudden rapid increase)

other noise vs. current

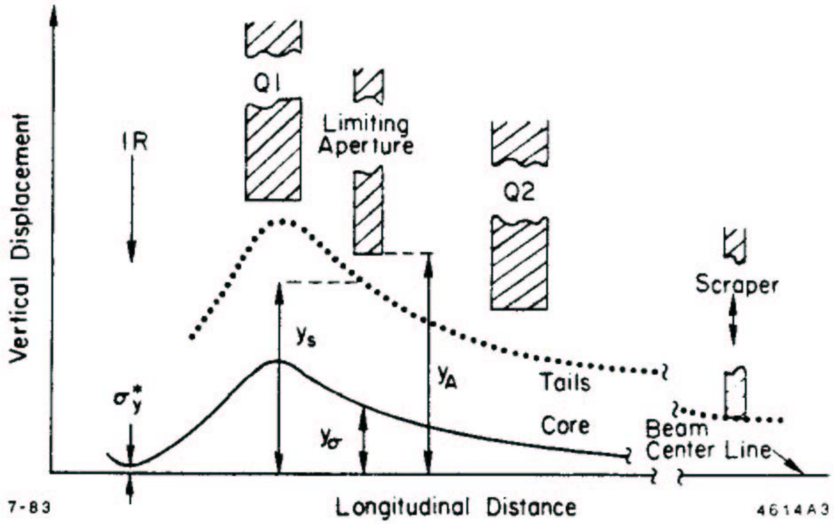
scraper position for 2 hr lifetime ~linearly increases

noise suddenly increases

core beam size gradually increases

scraper position for 2 hr lifetime suddenly increases

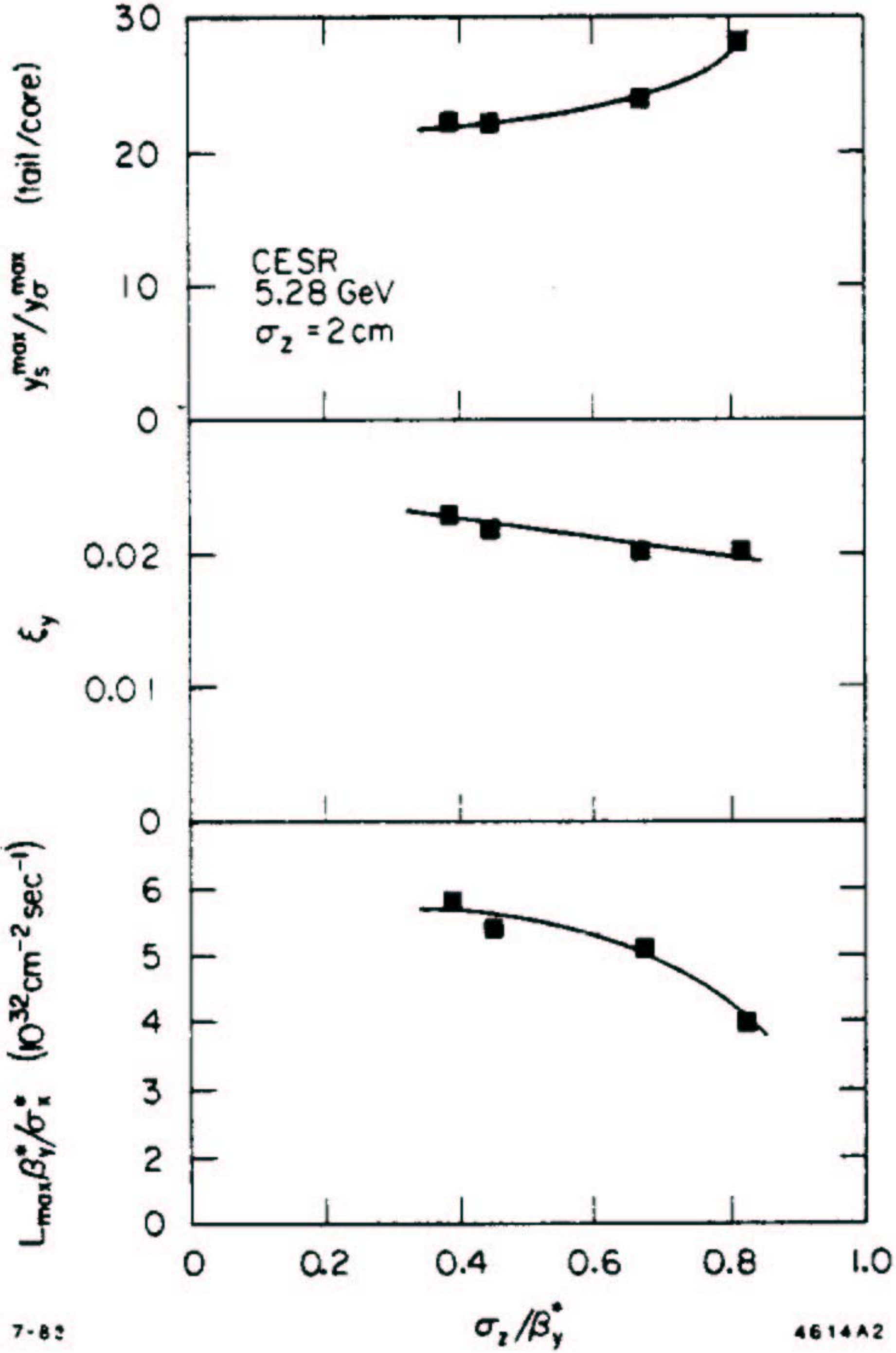
(Seeman, 1983)



Machine	Lattice (at maximum luminosity)	$\frac{y_A}{y_\sigma}$	$\frac{y_s}{y_A}$
SPEAR	TEM188/4A	22	0.83
SPEAR	TEM188/5	20	0.91
SPEAR	B188L28W	25	0.87
CESR	L3538.002	21	0.83
CESR	E99XX6.9A0	22	0.94
CESR	G99328.9A0	21	0.96
CESR	N9932B.9A1	24	0.92
CESR	N992BC.9A1	31	0.85
PETRA	7 GeV mini β	16	–
PETRA	11 GeV mini β	26	–
PEP	Spring 1981	17	–
PEP	Spring 1983	19	–
	(at low current)		
SPEAR	B188L28W	40	0.27
CESR	N9932B.9A1	48	0.57
PETRA	11 GeV mini β	46	–
PEP	Spring 1983	28	–

Seeman's conclusions:

(1) both core and tails increase dramatically with current; (2) scraper positions at peak current and max. luminosity consistent with physical aperture; (3) ratio of physical aperture to translated vertical beam size close to value of 20 in all cases but one



tails set
a limit to β_y
reduction:

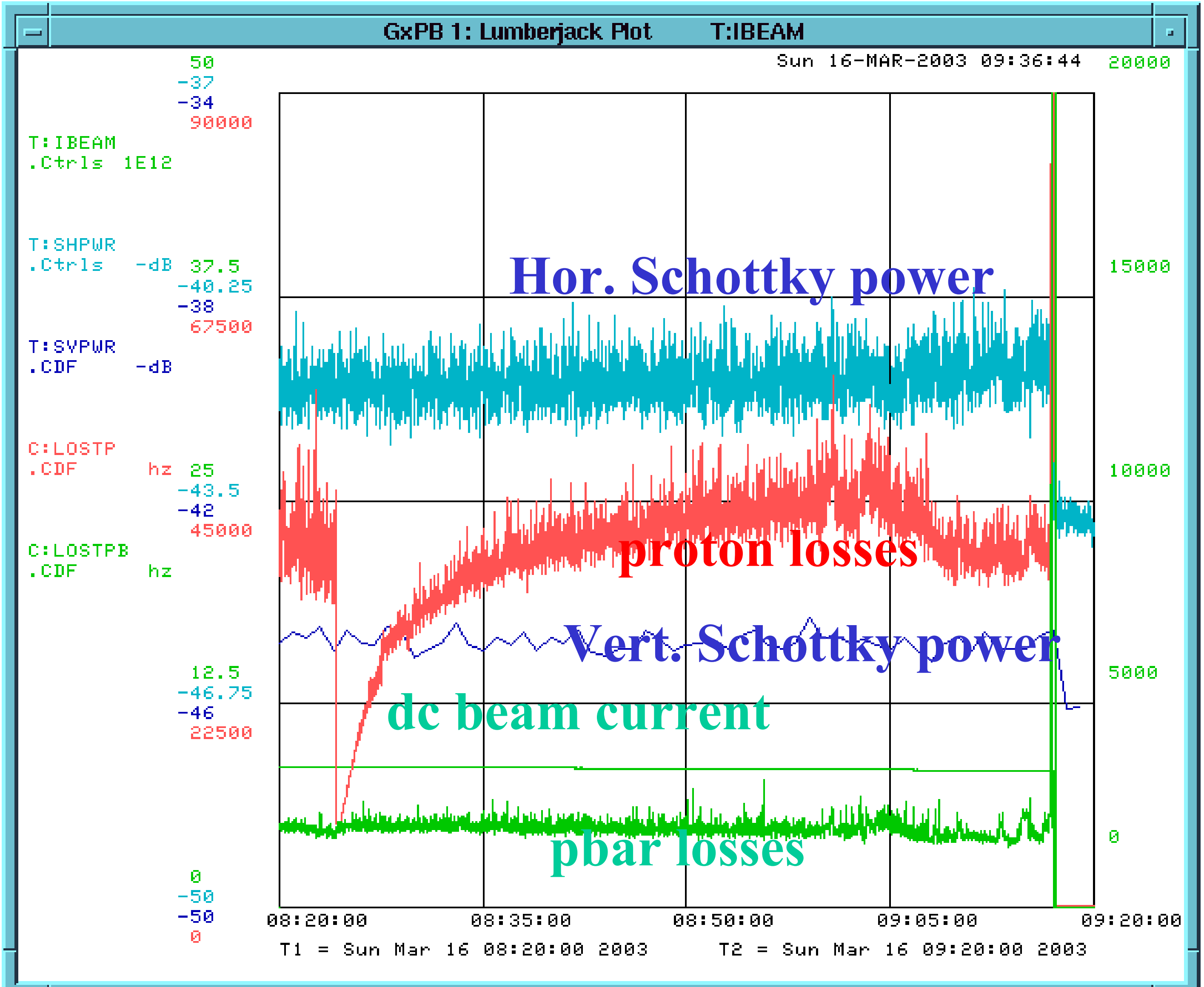
CESR measurements (left) show 12% luminosity loss from hourglass plus 30% from tails

(Seeman, 1983)

tails in hadron colliders

- particles ‘never’ come back
- they also cause background in experiments
- large losses can destroy collimators
- may quench a superconducting machine

Tevatron luminosity record store



excessive <u>proton losses</u> at start of store

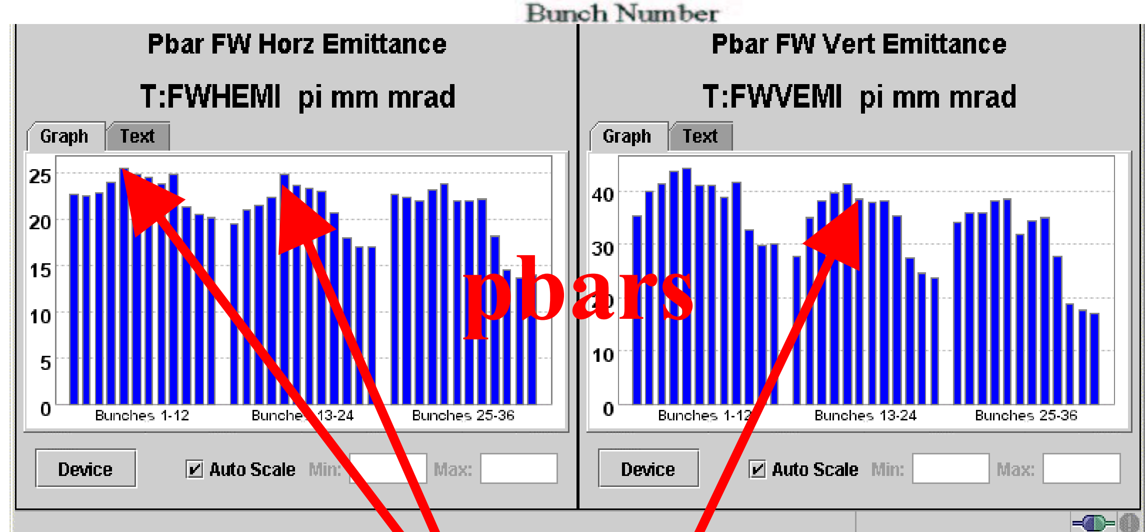
<u>quench after one hour</u> later when adjusting tune and coupling to minimize losses

(X.-L. Zhang)

large differences from bunch to bunch

emittance growth rate for different bunches

emittances of 36 bunches in the **Tevatron** at start of coast



scallop! (T. Sen)

candidate tail generating mechanisms

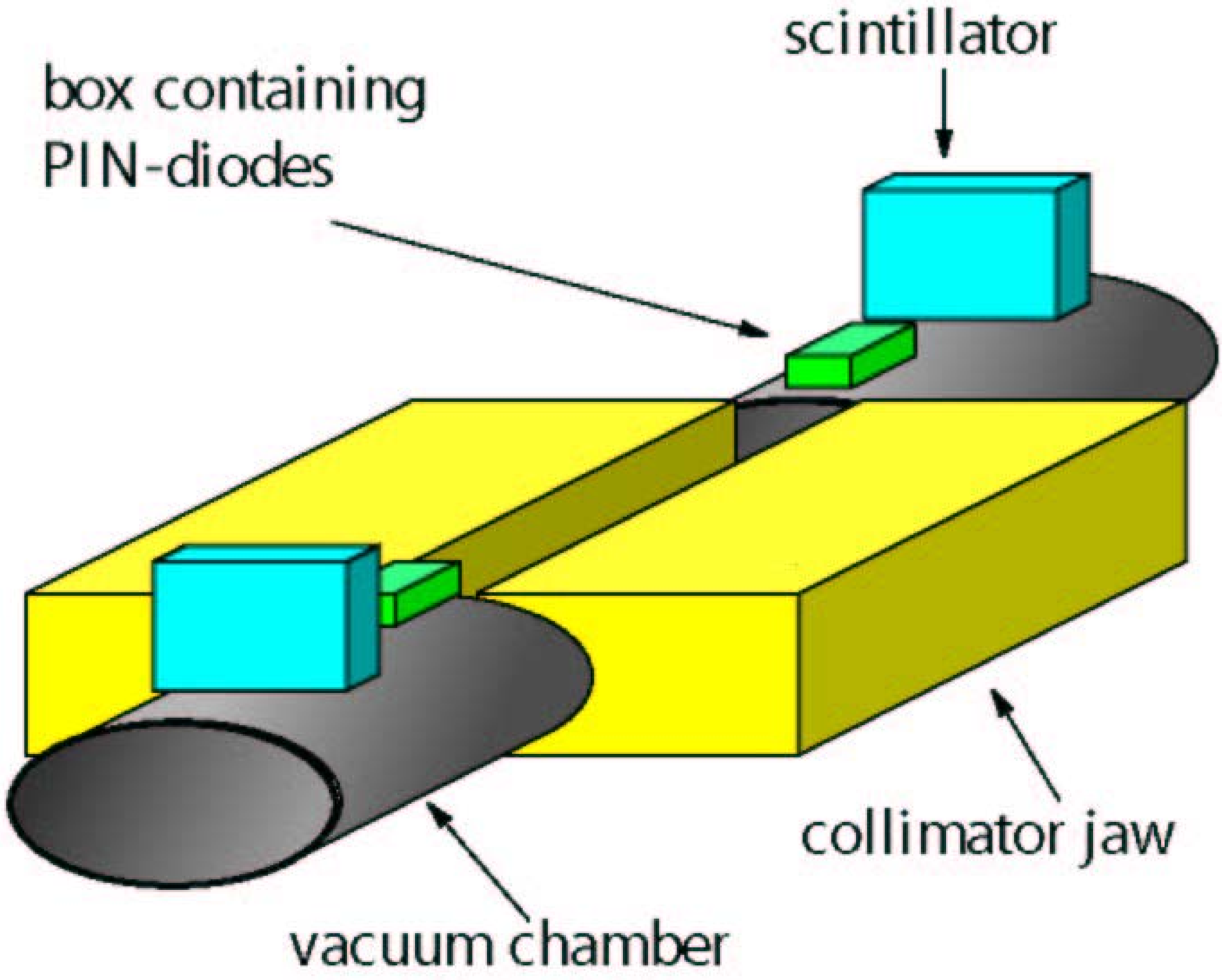
- b-b bremsstrahlung (Burkhardt et al, 1997) LEP
- stochastic diffusion (Cornelis, 1993) LEP
- Arnold diffusion (Chirikov, 1979)
- resonance trapping (Chao, Month, 1974)
- phase convection (Gerasimov, 1990)
- resonance streaming (Tennyson, 1980)

e+e- storage rings

- modulational diffusion (Chirikov, 1979)
- …

hadron colliders

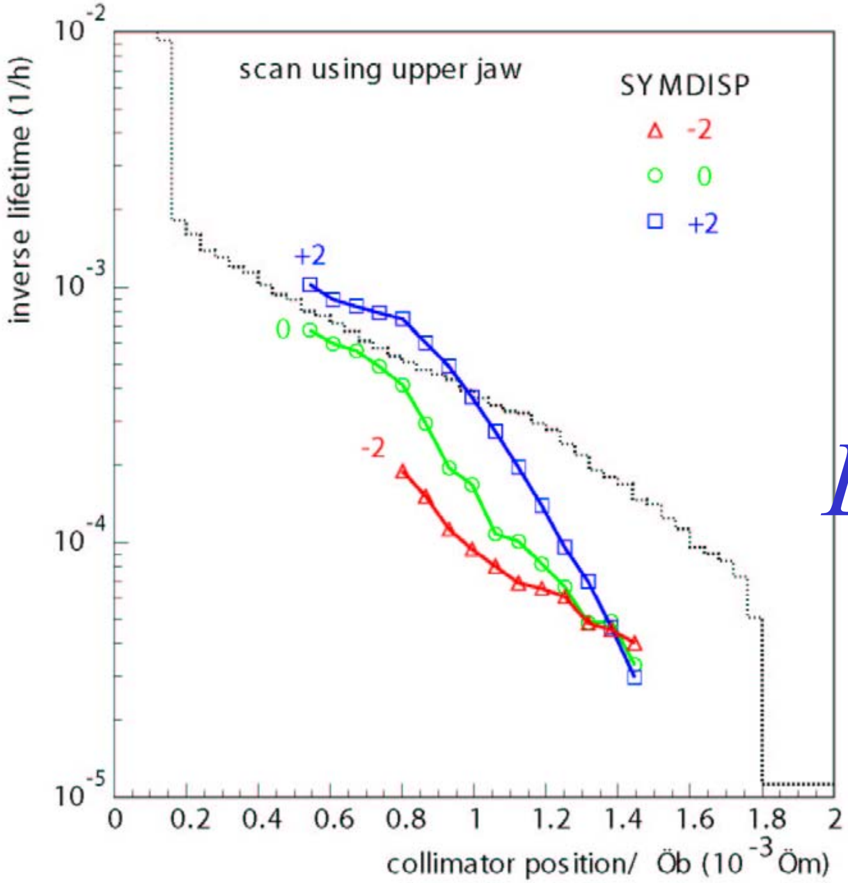
measurement of tails by collimator (LEP)

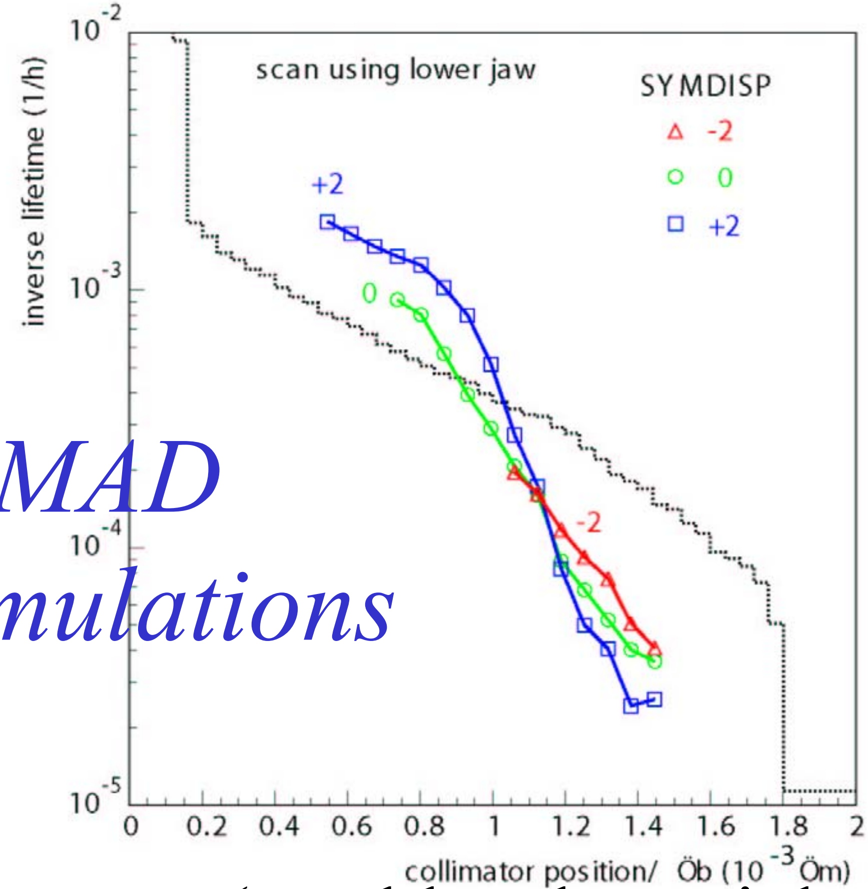


(Burkhardt, Reichel)

LEP: beam-beam bremsstrahlung

vertical beam tails in LEP for different vertical dispersion at the IPs at 46.6 GeV with ξ~0.025. dotted line gives simulation w/o dispersion





DIMAD simulations

(Burkhardt, Reichel)

incoherent 'scattering' processes

Events per collision per particle:

(1) incoherent beam-beam bremsstrahlung ($E_\gamma > E_c \equiv 4\gamma^2 \hbar c/\sigma_z$)

BB BS

LEP, KEKB prob.~10^{-9}/IP

$$\frac{dN}{dE_\gamma} \approx 0.4 \frac{1}{E_\gamma} \alpha \left(\frac{r_0^2 N_2}{\sigma_x \sigma_y} \right) \left[\ln \left(\frac{4\gamma^3 m_e c^2}{E_\gamma} \right) - \frac{1}{2} \right]$$

(V. Berestetskii et al)

(2) coherent bremsstrahlung ($E_\gamma < E_c \equiv 4\gamma^2 \hbar c/\sigma_z$)

CBS

?

$$\frac{dN}{dE_\gamma} \approx 0.2 \frac{1}{E_\gamma} \alpha \left(\frac{r_0 N_2}{\sigma_x} \right)^2$$

(V. Serbo et al)

(3) pair production and e$^-$ capture (reducing ion charge by 1):

pair prod. +e$^-$ capt.

LHC with ions!

$$N \approx \left(\frac{N_2}{4\pi\sigma_x\sigma_y} \right) \frac{33\pi Z^8 \alpha^6 r_e^2}{10} \frac{1}{e^{2\pi\alpha Z} - 1} \left[\ln \left(\frac{\delta(\gamma^2 - 1)}{2} \right) - \frac{5}{3} \right]$$

(S. Klein)

(4) nuclear excitation and n emission (reducing ion mass by 1, and recoil):

nuclear excitation

LHC with ions!

$$N \approx \left(\frac{N_2}{4\pi\sigma_x\sigma_y} \right) (3.42\ \mu\text{barn}) \frac{(A-Z)Z^3}{A^{2/3}} \ln(2\gamma^2 - 1)$$

(S. Klein)

(N_2 is bunch population of other beam)

partial & total cross sections in barn for collisions of identical ions at LHC energy

	σ_H	σ_{EMD}	σ_{ECPP}	σ_{tot}
Hydrogen	0.105	0	4.25×10^{-11}	0.105
Helium	0.35	0.002	$1.\times 10^{-8}$	0.352
Oxygen	1.5	0.13	0.00016	1.63016
Argon	3.1	1.7	0.04	4.84
Krypton	4.5	15.5	3.	23.
Indium	5.5	44.5	18.5	68.5
Lead	8	225.	280.756	513.756

$\delta_p=-1/(A-1)$ $=-5\times10^{-3}$ $\delta_p=1/(Z-1)$ $=12\times10^{-3}$

for Pb

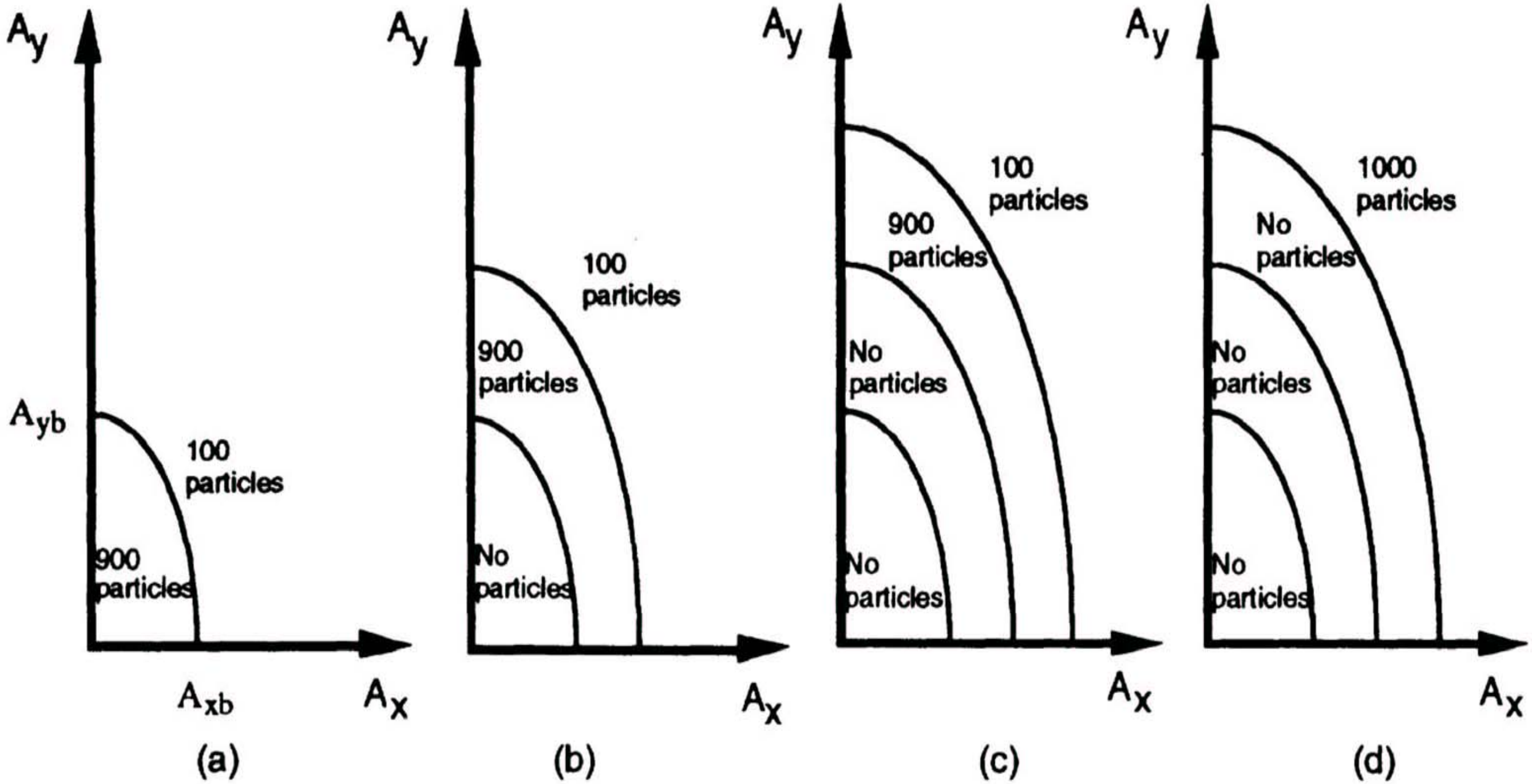
(J. Jowett, B. Jeanneret)

simulation approaches

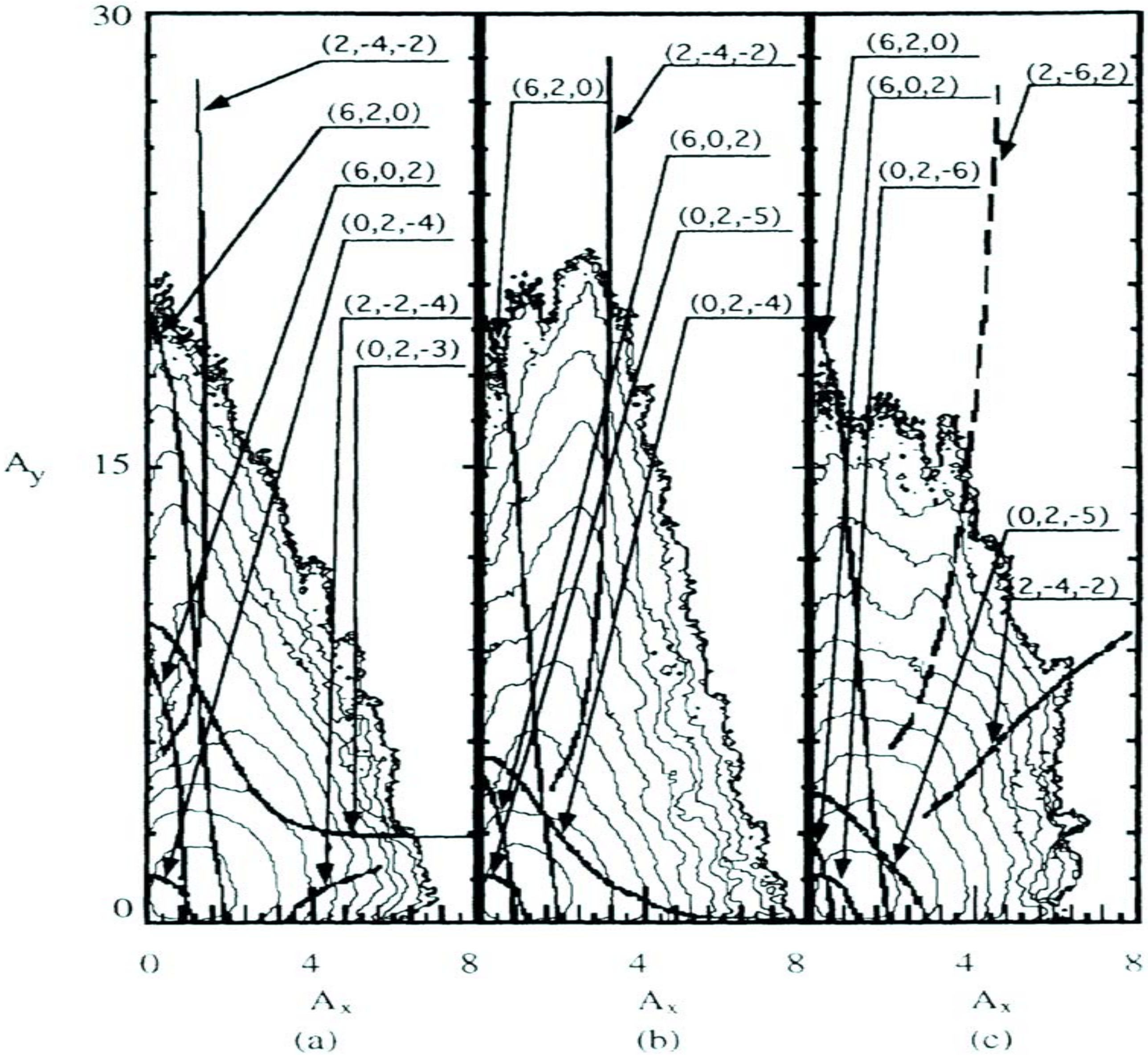
- in Novosibirsk 1989 J. Irwin proposed scheme based on 'self-generated boundary conditions' (~10^8 particle turns)
- implemented by D. Shatilov 1992 ***lifetrac*** (~10^7 particle turns)
- and by T. Chen, J. Irwin, R. Siemann, ~1993
  these codes can include frequent small-angle scattering
- E.-S. Kim & K. Hirata developed macroparticle scheme for simulation of large rare scattering + beam-beam, 1997 (~$2\text{x}10^9$ particle turns)
- brute force (J. Tennyson TRS; K. Ohmi's PIC code; ~ $5\text{x}10^8$ - $6\text{x}10^9$ particle turns)

above codes are mainly for lepton colliders

each step gains a factor of 10

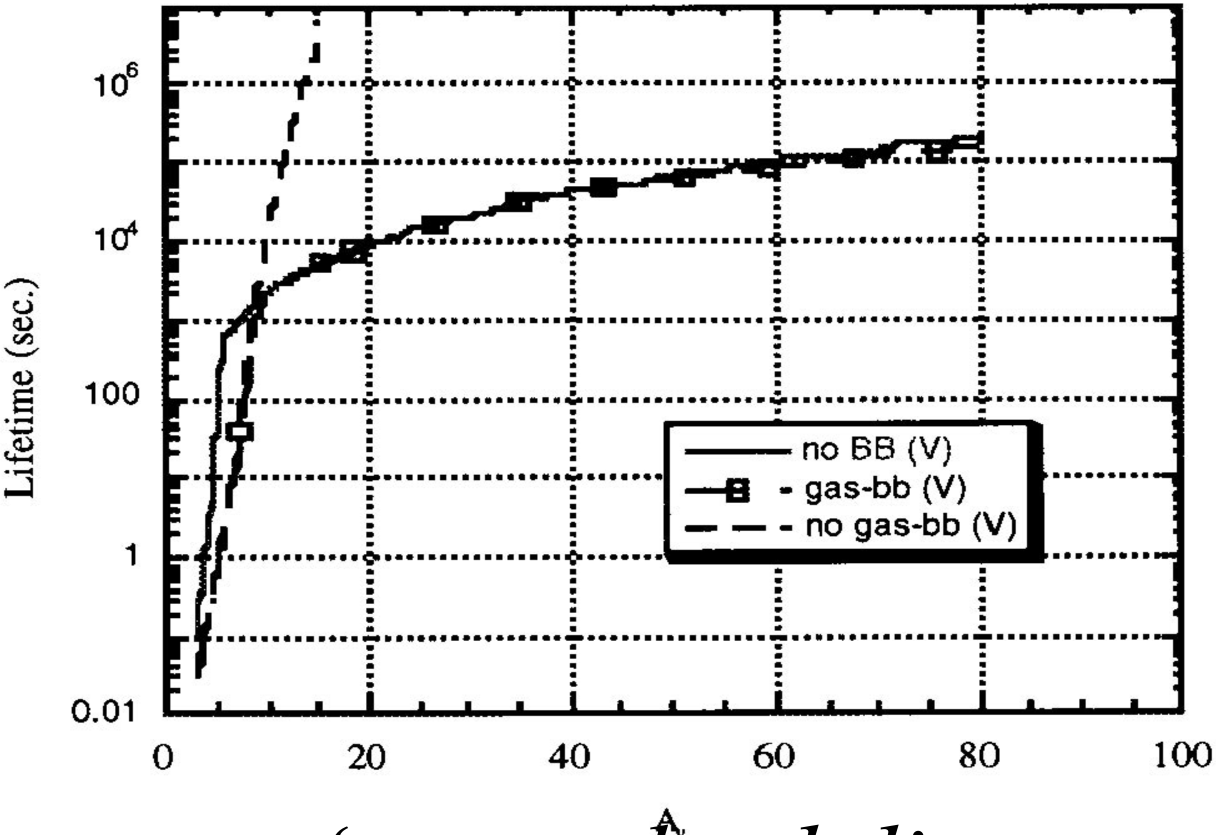


schematic of Irwin’s simulation process;
keys: (1) randomness, (2) equilibrium



resonance lines beam distributions for different Q_s showing role of resonances in tail formation

(T. Chen, J. Irwin, R. Siemann, 1993)



beam-beam + gas scattering

(T. Chen, J. Irwin, R. Siemann, 1993)

some 'unresolved discrepancies':

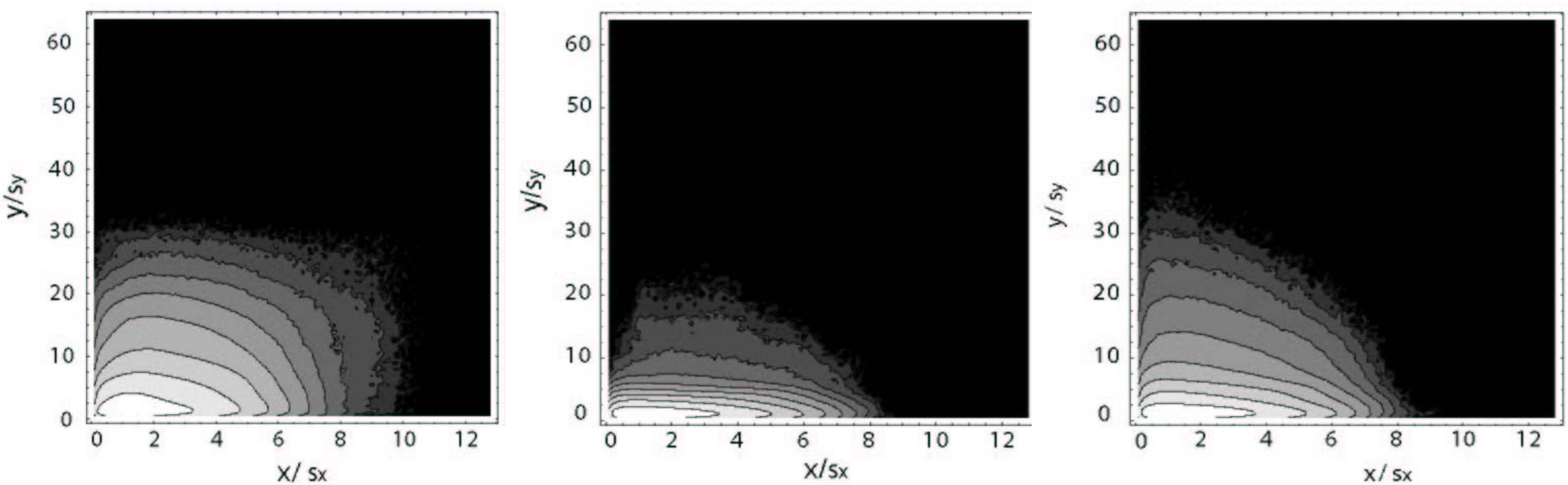
for PEP-II no mutual enhancement found here, while Shatilov/Zholents saw a large effect!? on the other hand, Kim/Hirata determined that bb bremsstrahlung is dominant for KEKB!?

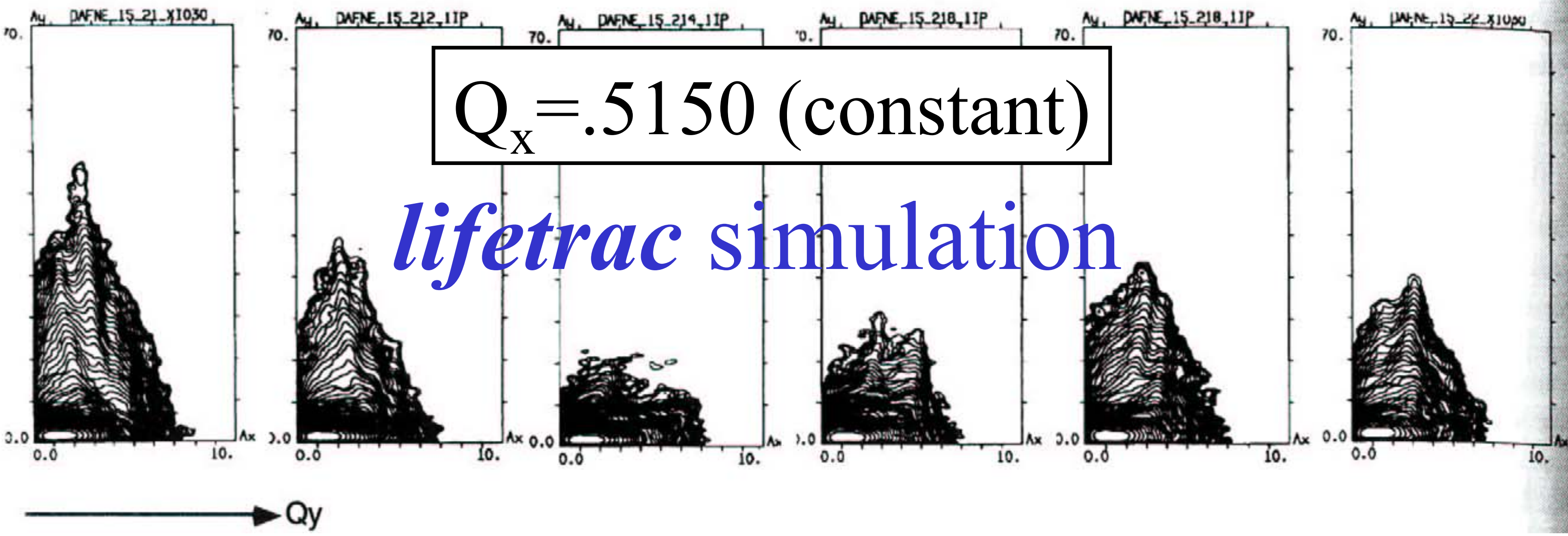
brute force weak-strong simulations provides estimate of beam halo without special technique, thanks to increased computer power: 5×10^8 particle*turns, 10 longitudinal slices (K. Ohmi)

present KEKB
θ/2=11 mrad

present KEKB
but head-on

Super-KEKB
head-on





Q_x=.5150 (constant)

lifetrac simulation

Q_y=5.210 5.214 **best sim.** Q_y=5.220

Q_x^-	Q_y^-	I^+ (mA)	I^- (mA)	τ^- (s)
5.1526	5.2113	15	5	2100
5.1513	5.2126	16.5	5.8	1500
5.1505	5.2124	15.8	5.6	3200
5.1505	5.2141	15.3	5.5	4000
5.1500	5.2141	13.9	5.9	4570

DAΦNE **measured** lifetime vs. tune

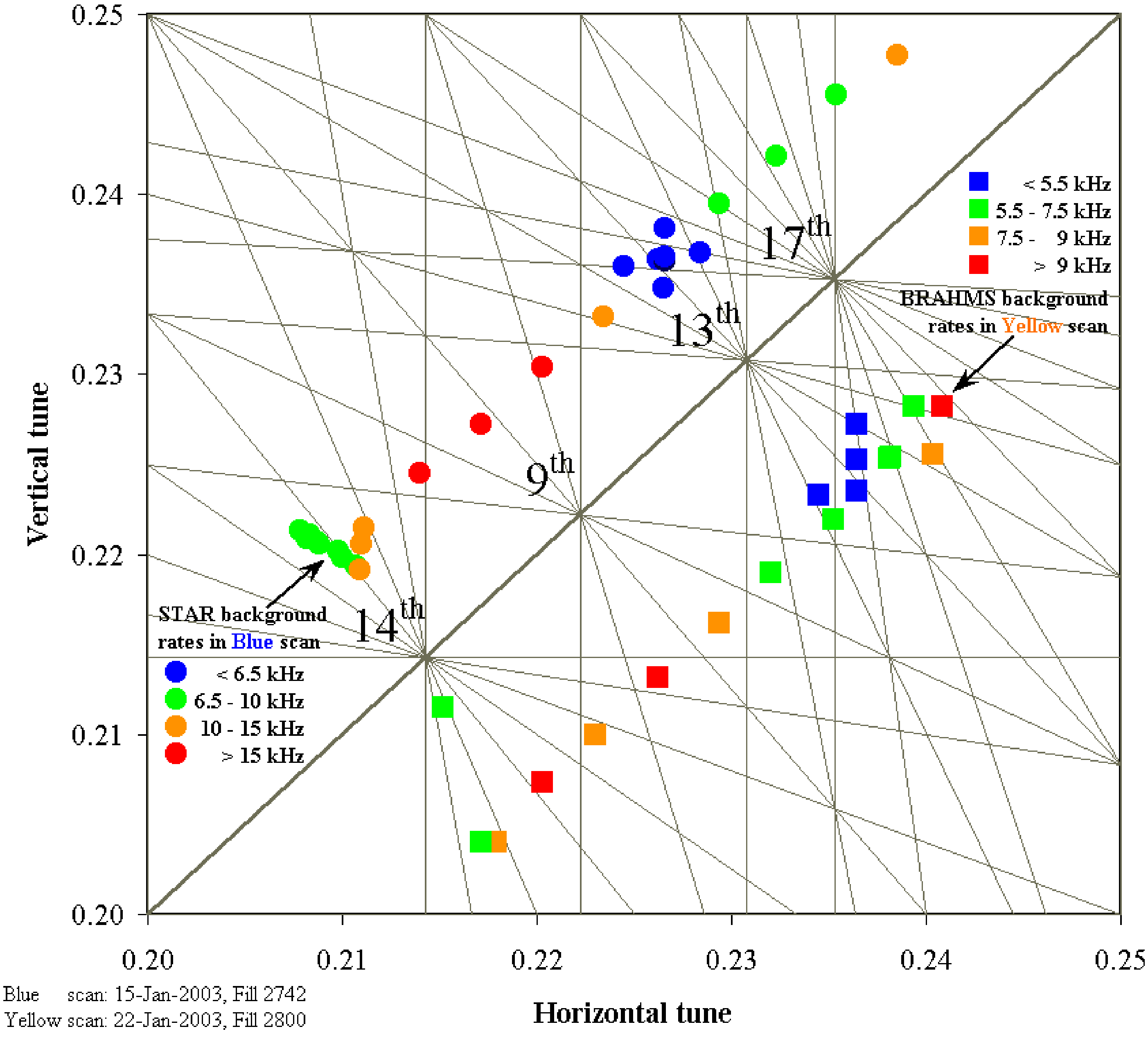
best meas. lifetime

tails are sensitive to the tune

ISR nonl. lens:	**$\|\delta Q\| << 0.002$**	Keil et al., 1975
SPS	**$\|\delta Q\| < 0.001$**	Meddahi, Cornelis, 1991
HERA	**$\|\delta Q\| < 0.002$**	Willeke, 1997
VEPP-4	**$\|\delta Q\| < 0.001$**	Temnykh, 1989
DAFNE	**$\|\delta Q\| < 0.001$**	Boscolo et al., 1999
KEKB	**$\|\delta Q\| < 0.001$**	Ohmi et al, 2003
LEP	**$\|\delta Q\| < 0.002$**	Burkhardt

beam lifetimes and *tails* are sensitive to tune variations much smaller than tune spread; similar tolerance for leptons & hadrons

background versus tune in RHIC

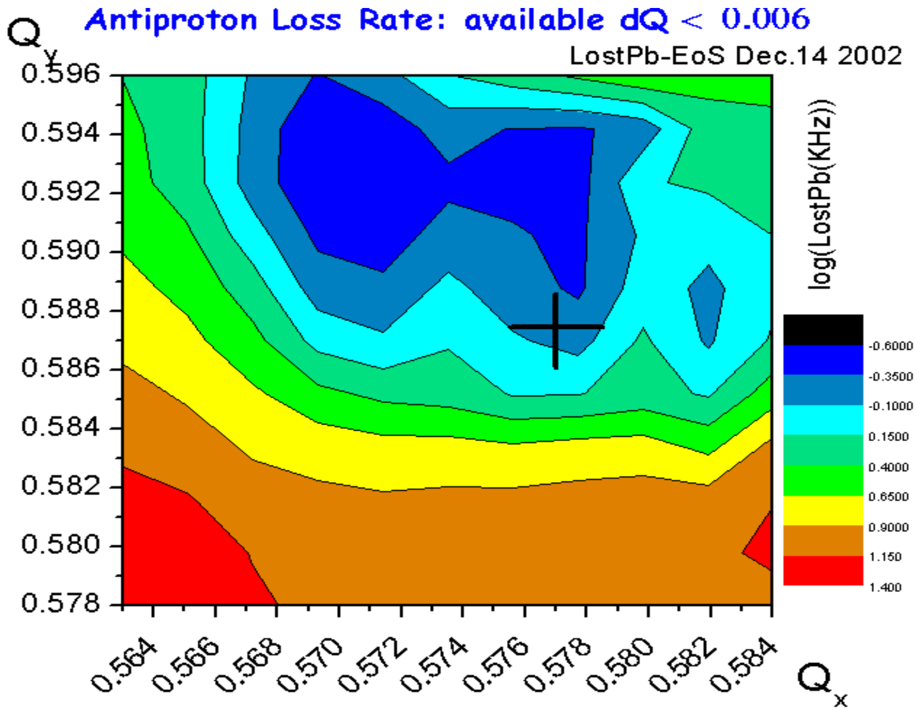


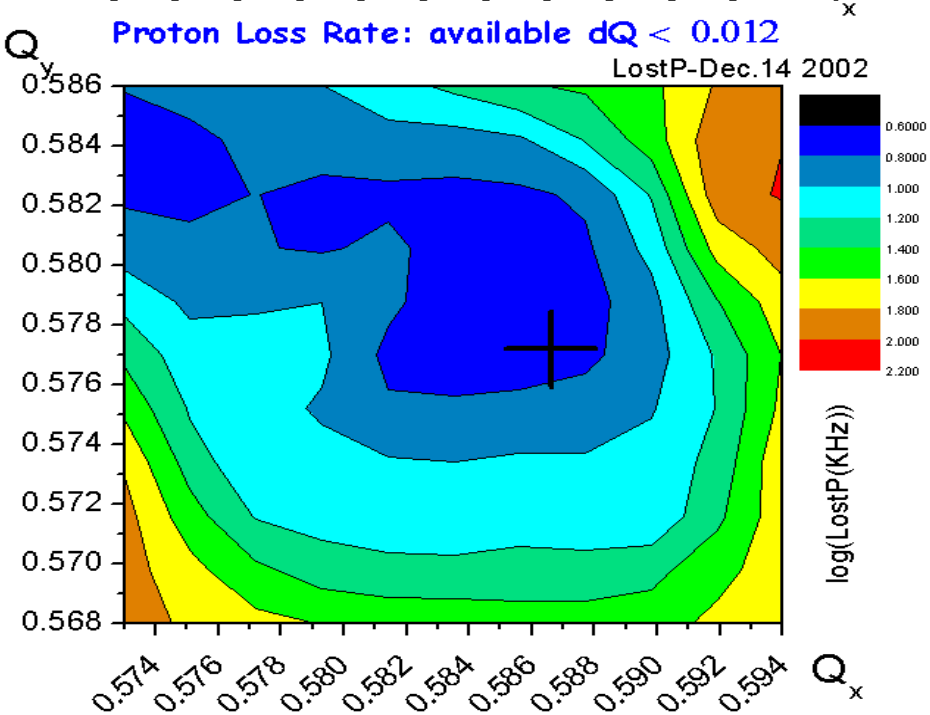
Blue scan: 15-Jan-2003, Fill 2742
Yellow scan: 22-Jan-2003, Fill 2800

result of tune scans (13th order resonance much better than 17th order!?)

$$mQ_x + nQ_y = q$$

(W. Fischer, 2003)



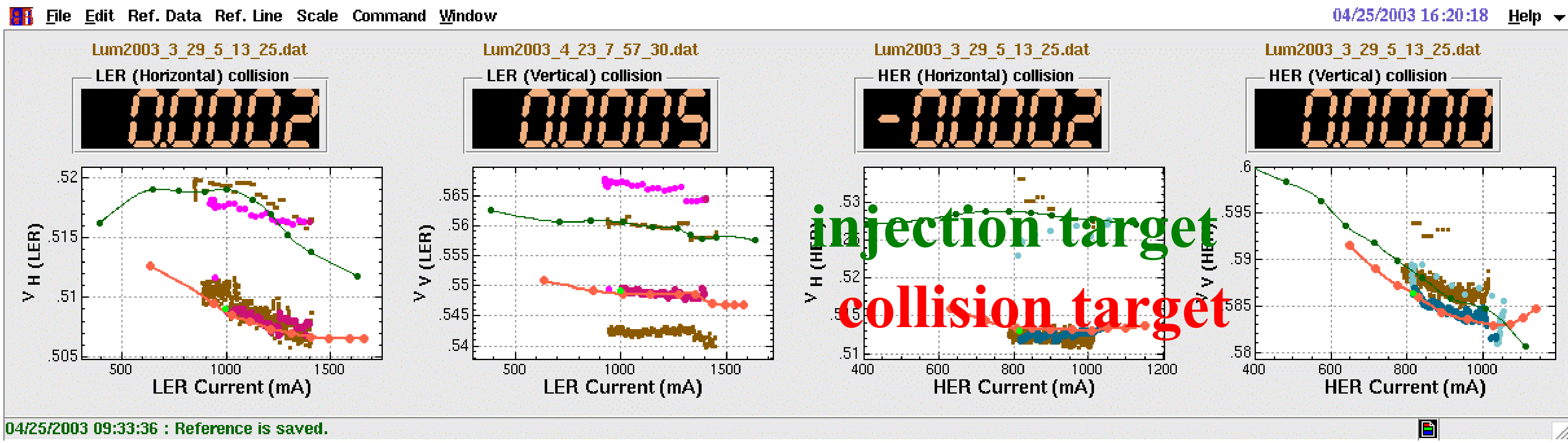


p & pbar loss-rate vs. tunes in the **Tevatron**

(T. Sen, M. Xiao, X. Zhang)

emittance exchange on coupling resonance only with pbars (beam-beam driven coupling)

KEKB tune feedback (K. Ohmi)

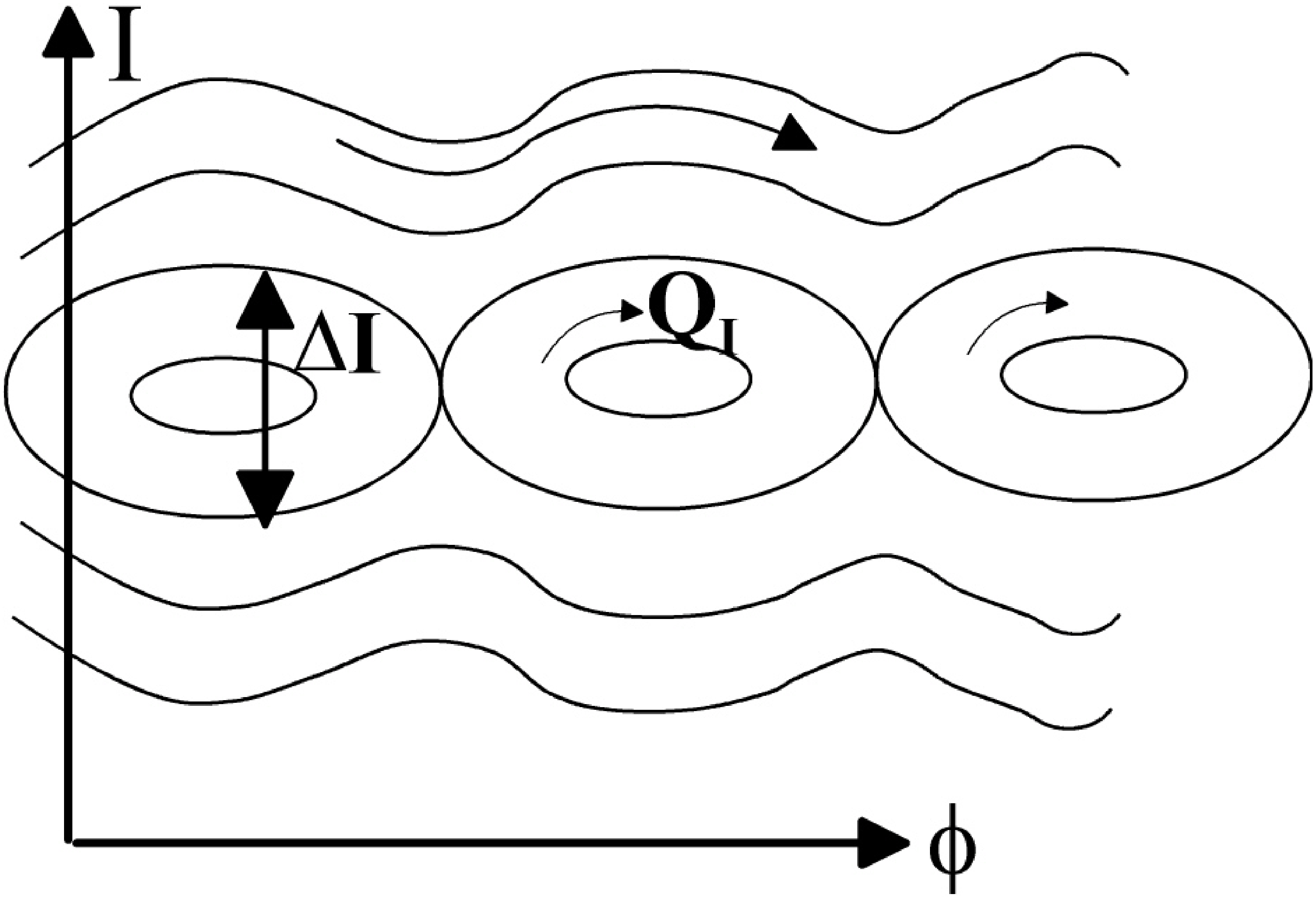


automatic continuous tune control <0.001!

target value depends on current (curves)

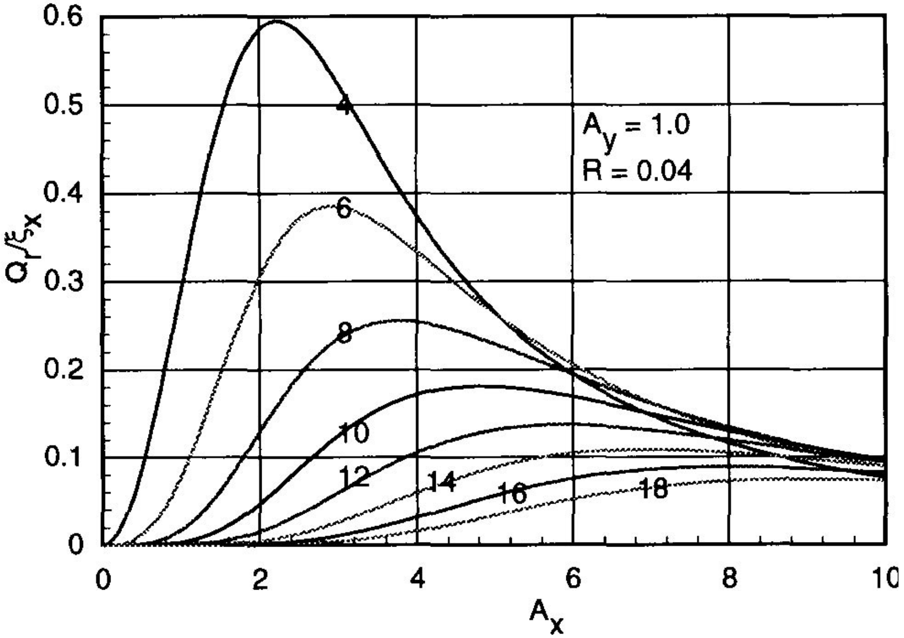
uses tune from non-colliding pilots

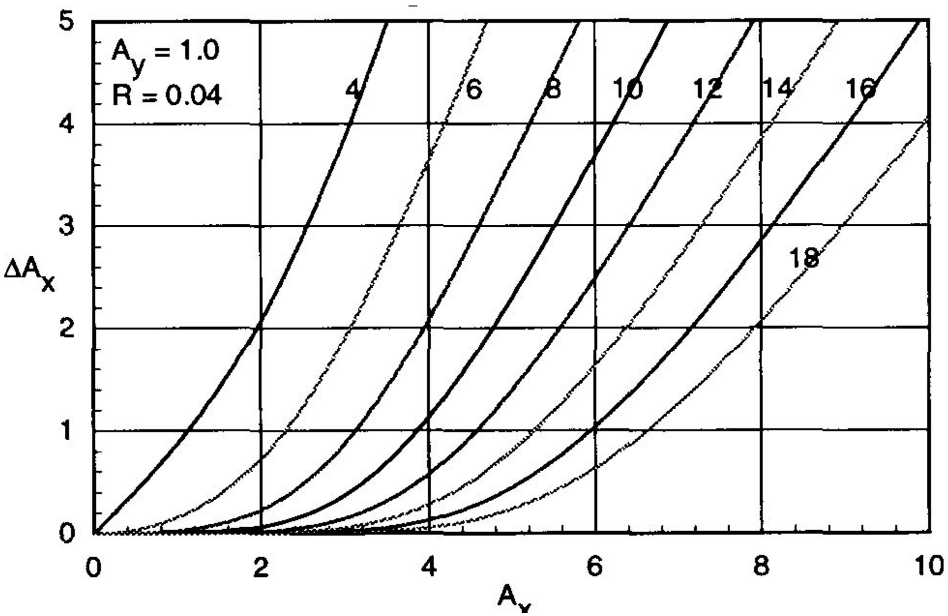
different curves for injection & collision



schematic of **resonance** of total **width** **ΔI** and **island tune Q_I**

island tune resonance width

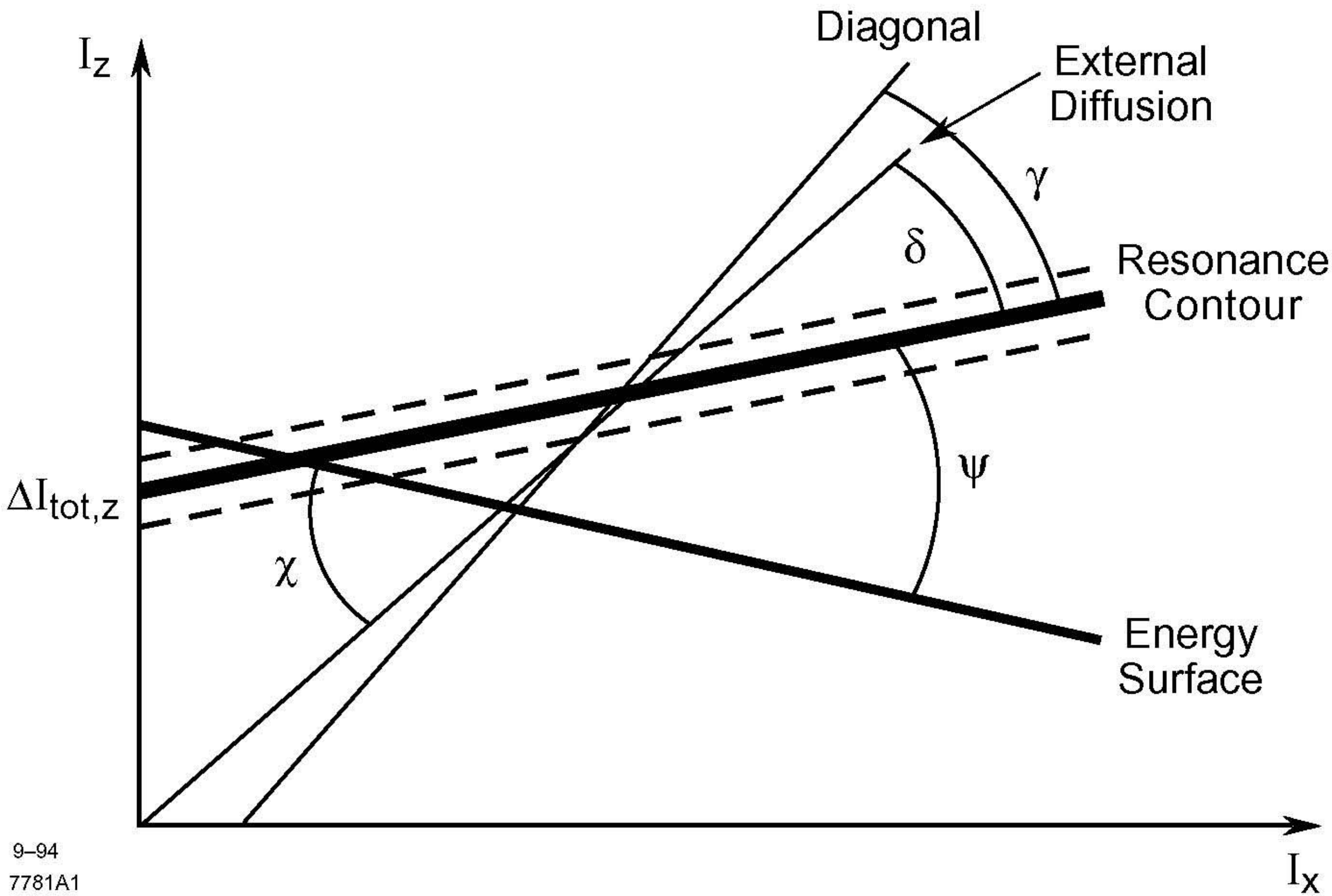




vs. amplitude vs. amplitude

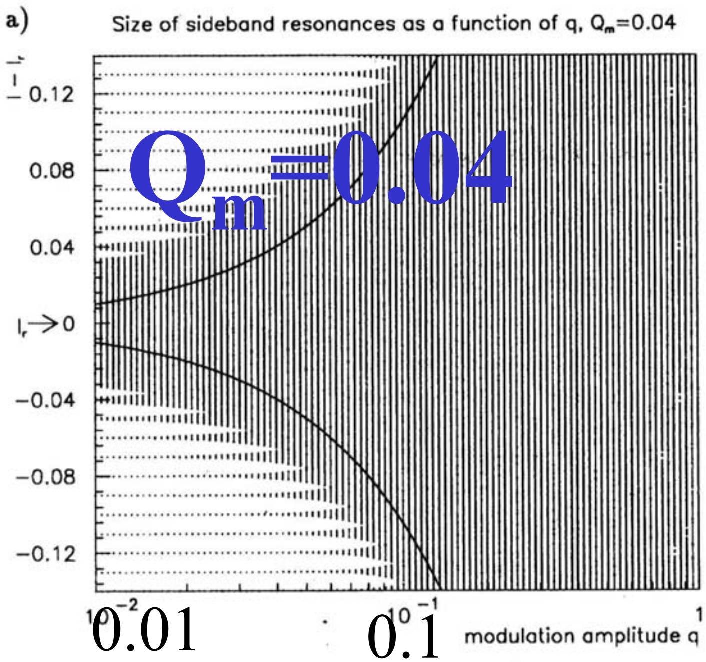
(T. Chen, J. Irwin, R. Siemann, 1993)

resonance streaming (Tennyson,1981)



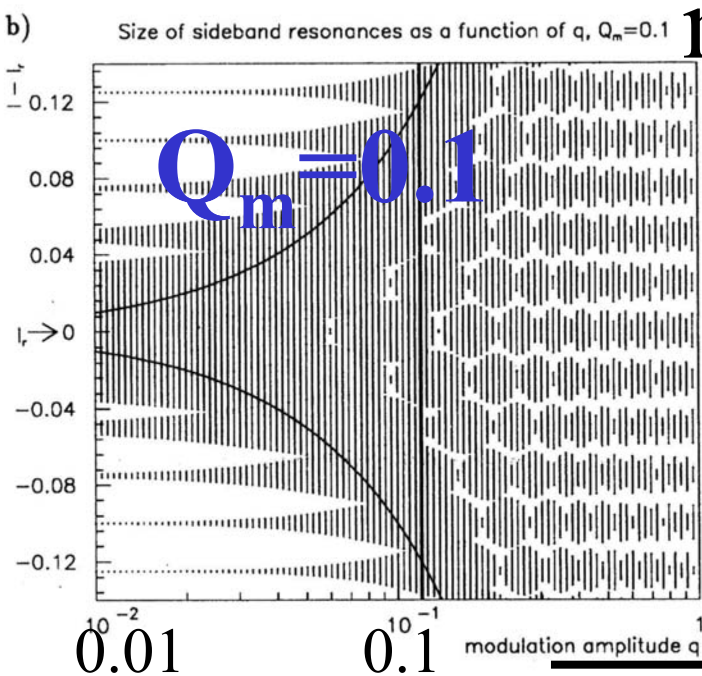
enhanced diffusion: $D \sim D_{ext} \sin^2 \chi / \sin^2 \psi$

Q_I~0.05



I

modulation depth q



I

tune modulation

→ sidebands

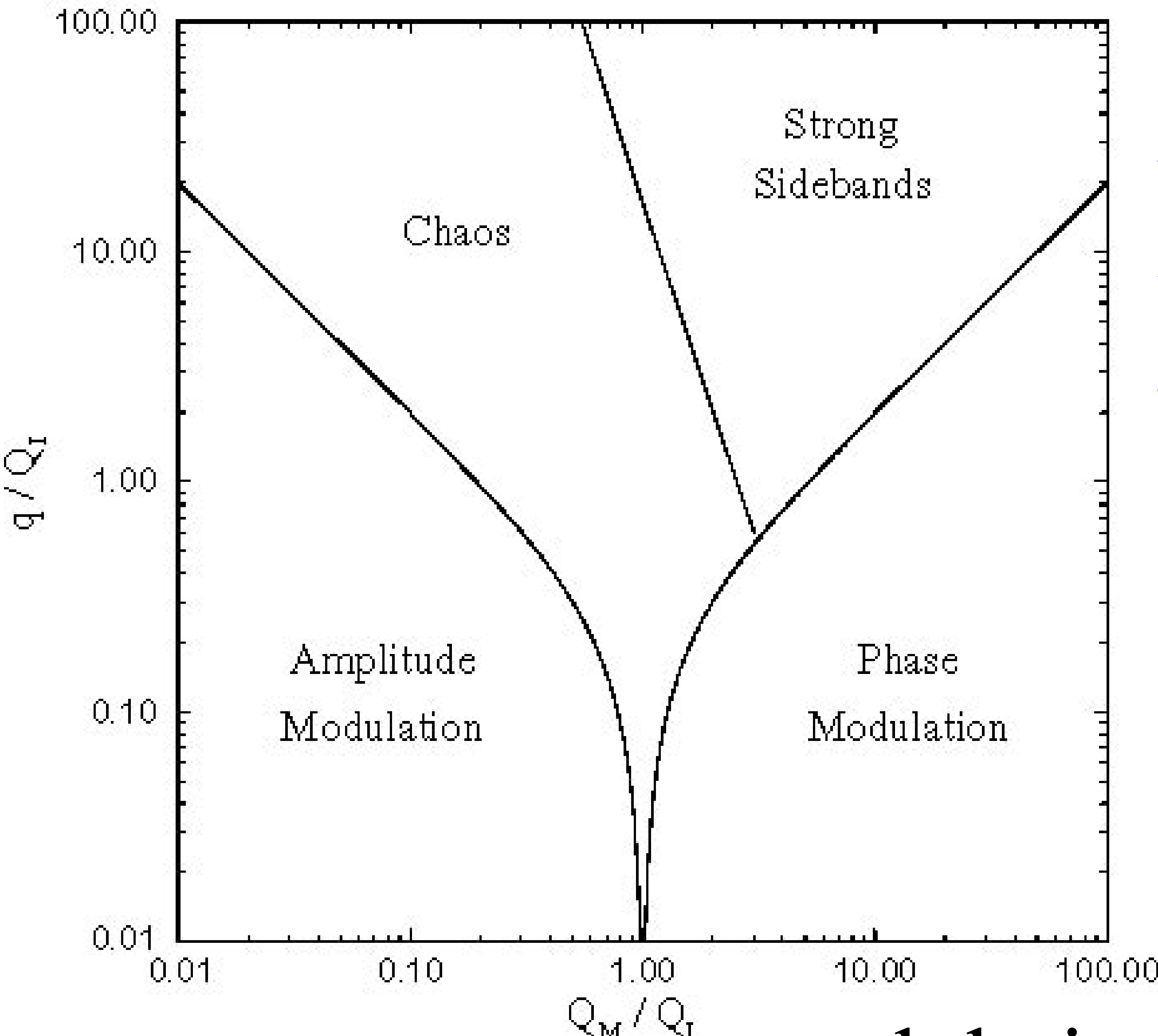
& possibly resonance overlap

2 examples

modulation depth q

modulation depth

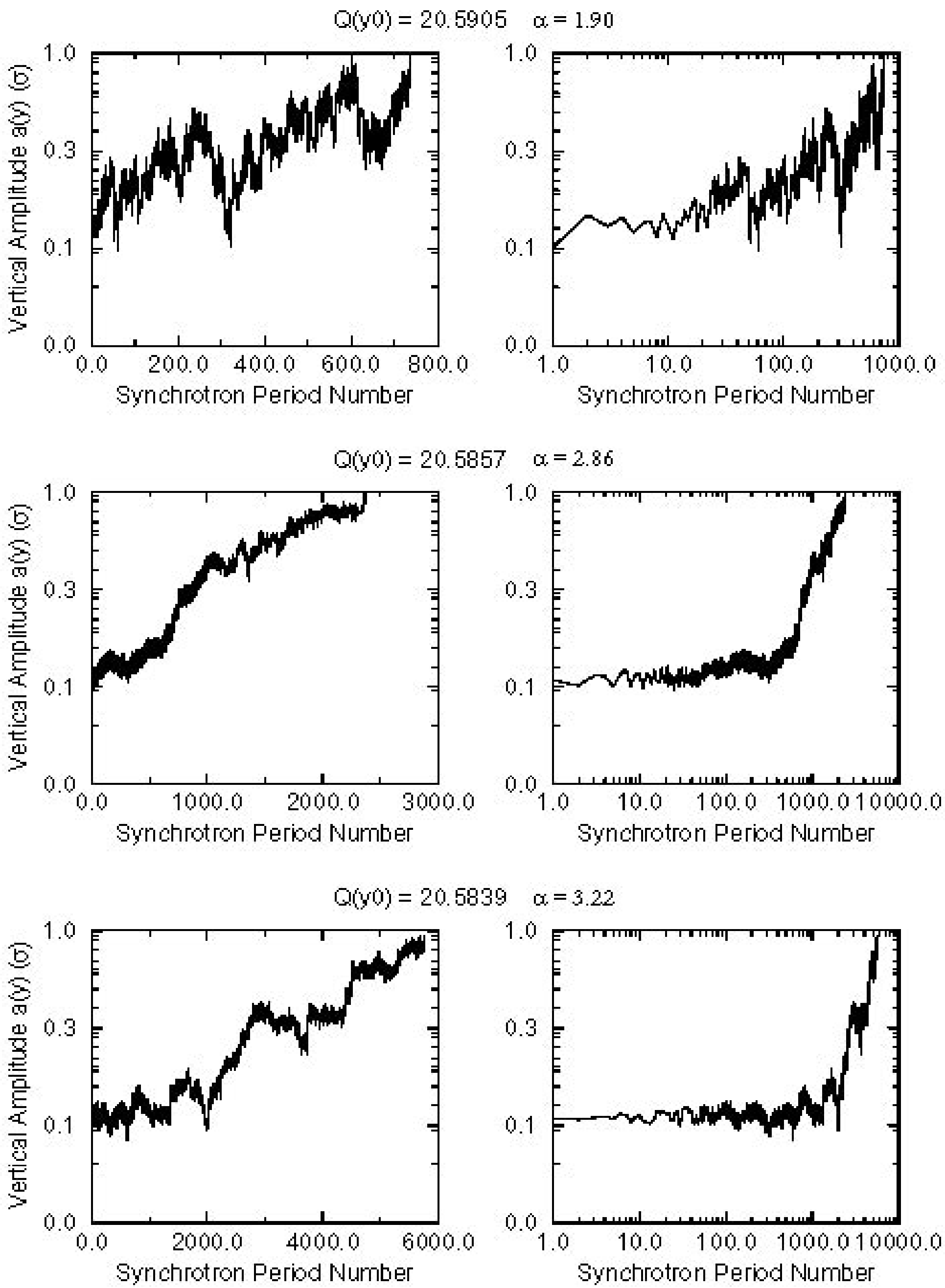
(S. Peggs)

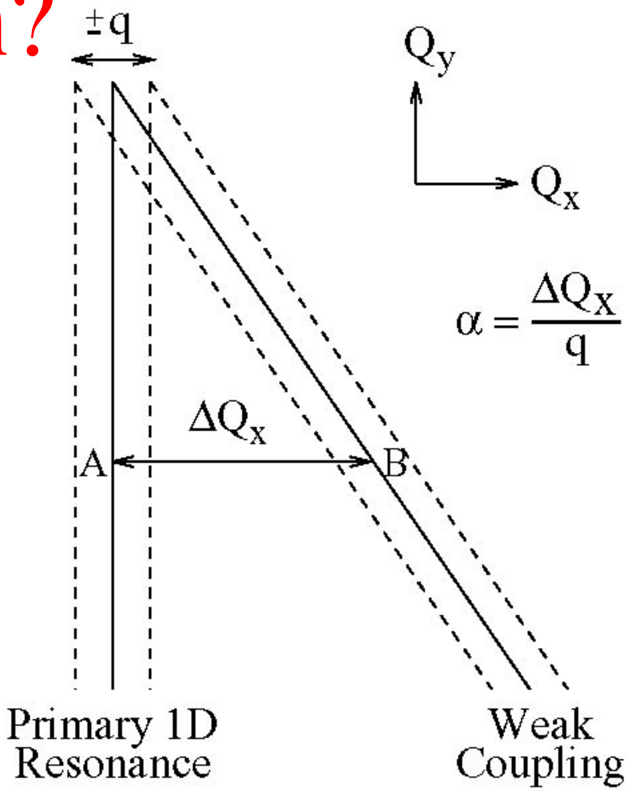


tune modulation near the island tune is harmful

modulation frequency

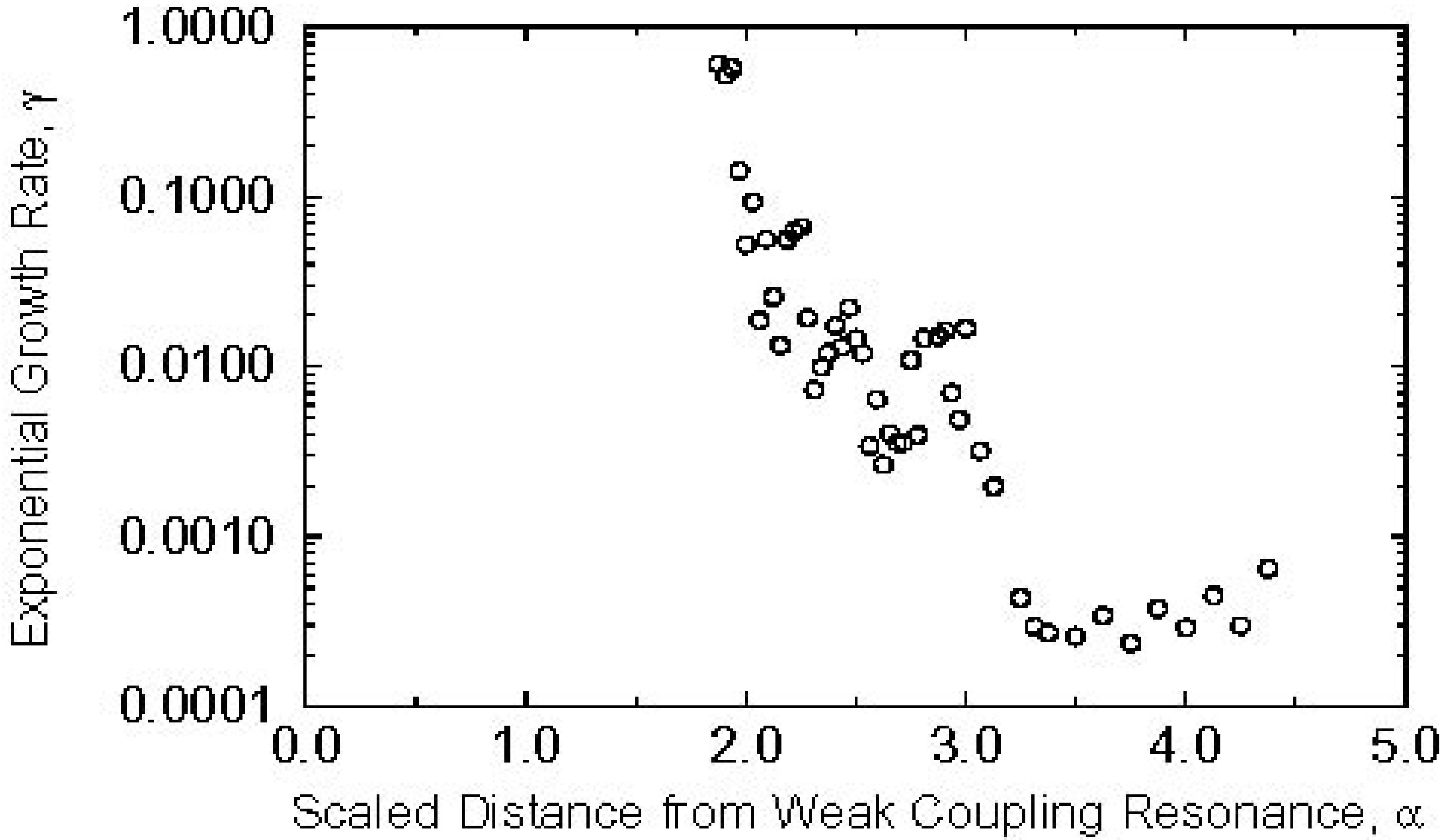
modulational diffusion?





growth is exponential and not $\sim t^{1/2}$ as predicted by theory of mod. diffusion!

(Satogata, 1993)



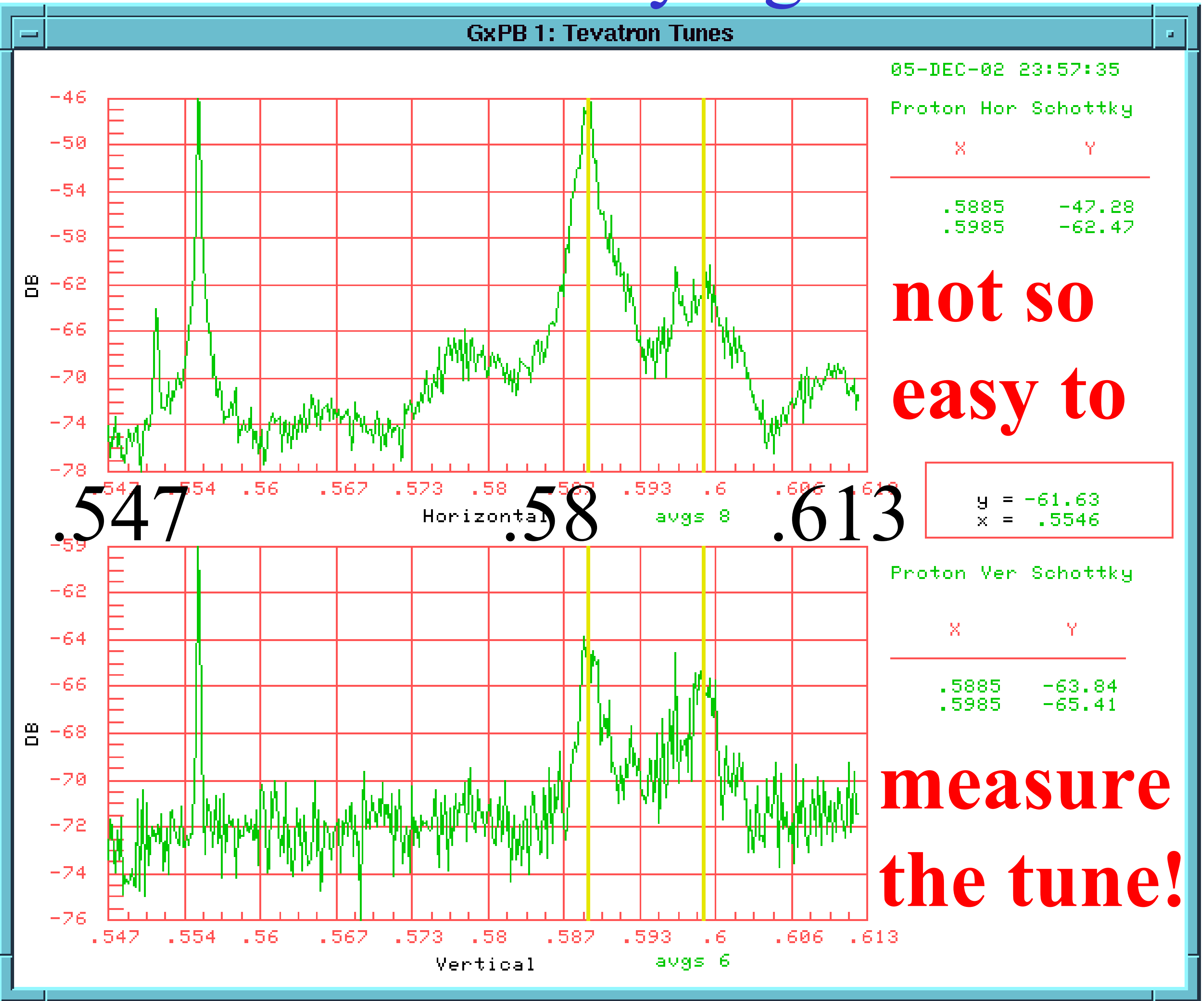
jumps in growth rate at values α=2 and α=3, while standard theory predicts cliffs at every 2nd integer only

(Satogata, 1993)

thus available analytical theory fails to describe simple simulation of beam-beam & tune modulation!

but now back to measurements…

Tevatron Schottky signals in collision



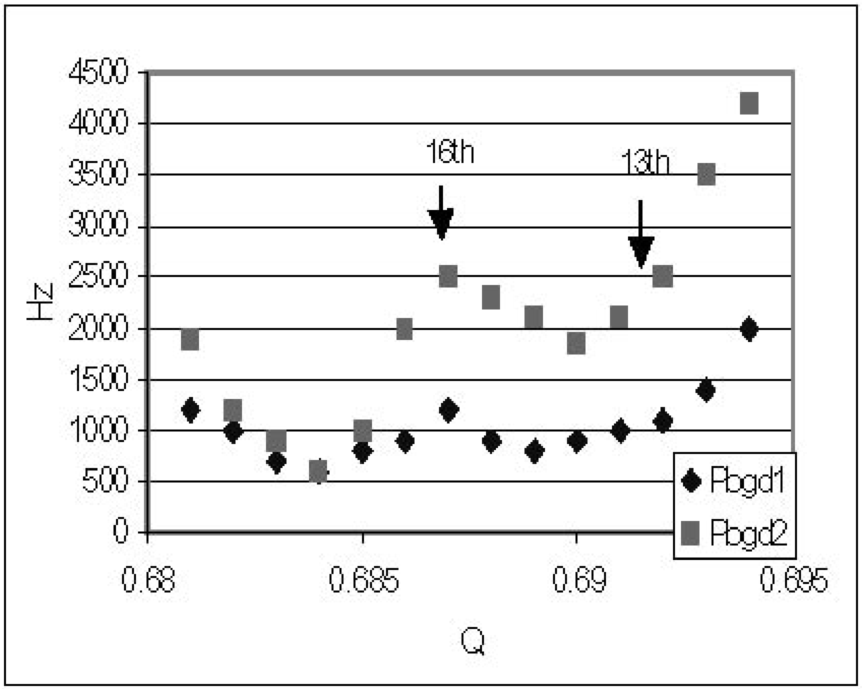
proton x

not so easy to measure the tune!

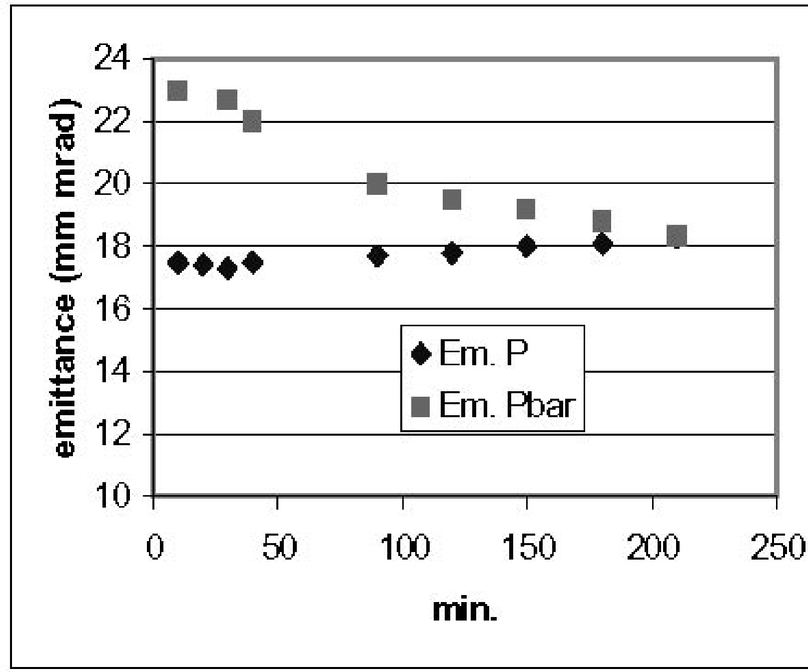
pbar x

influence of beam size: SPS

p background before (pbgd1) & after (pbgd2) ε (pbar) reduction by 30%



evolution of ε (pbar) and ε (p) during the first 200 minutes of a coast



smaller beam more harmful!

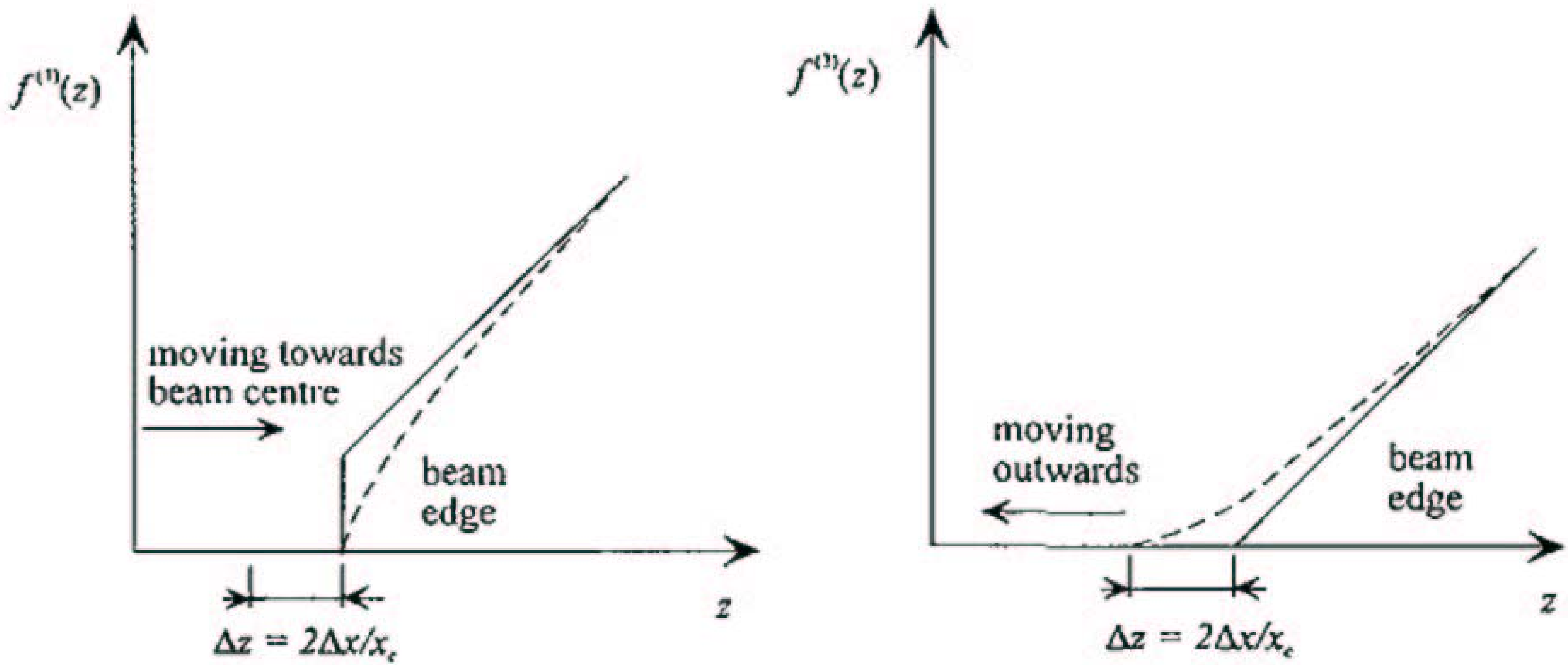
fast loss at large amplitudes (Meddahi, Cornelis, et al)

how well can we describe the proton tail growth by a diffusion equation?

- good local fits in HERA
- inconsistent with various tracking simulations (e.g., any survival plot versus

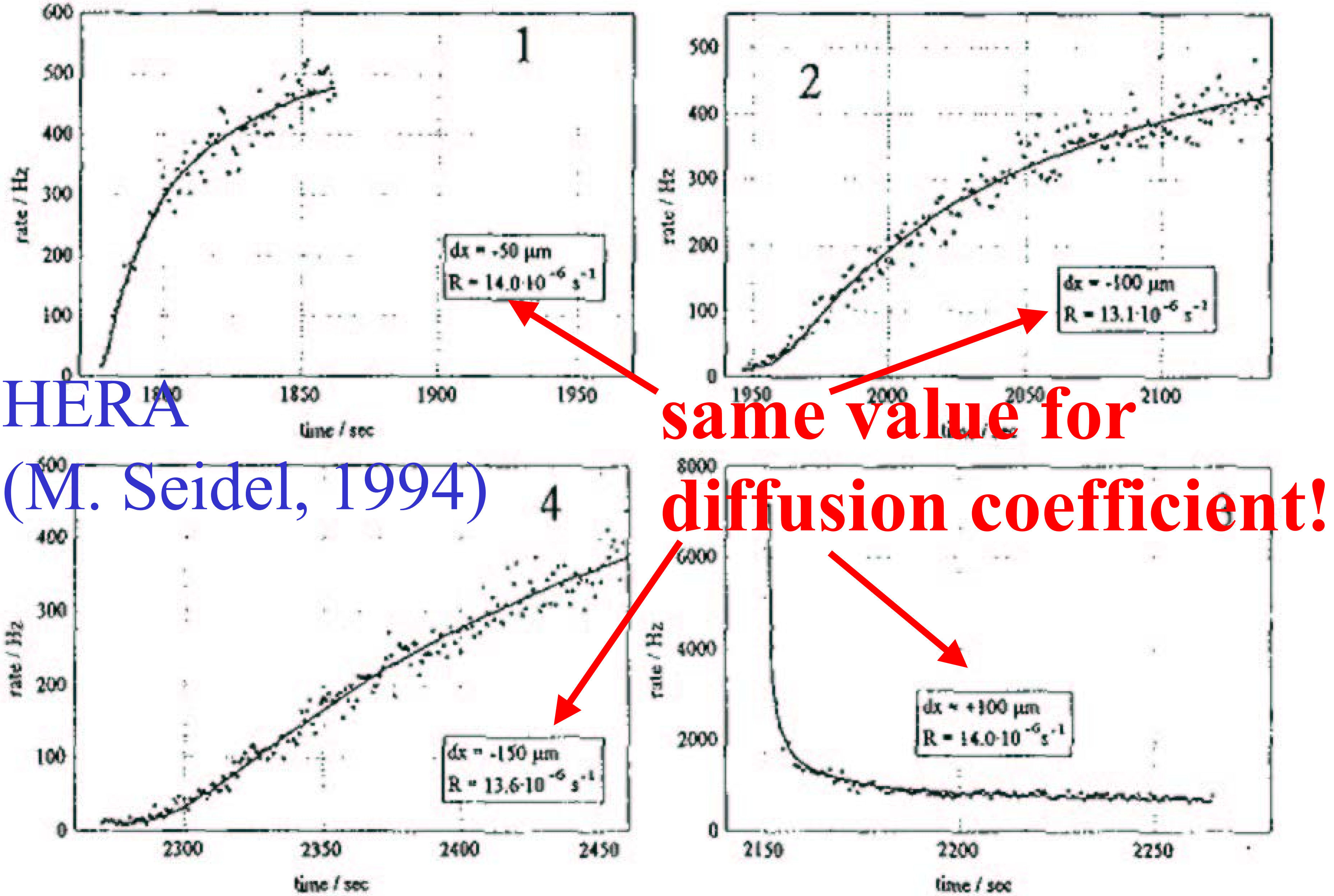
  no. of turns, or beam-beam model of Peggs & Satogata)
- inconsistent with SPS scraper measurements
- A. Gerasimov suggested to construct a 'jump and diffusion' model (1992)

‘diffusion measurement’ (M. Seidel, 1994)



initial distributions for collimator moving inwards and outwards; dotted lines sketch distributions after some relaxation

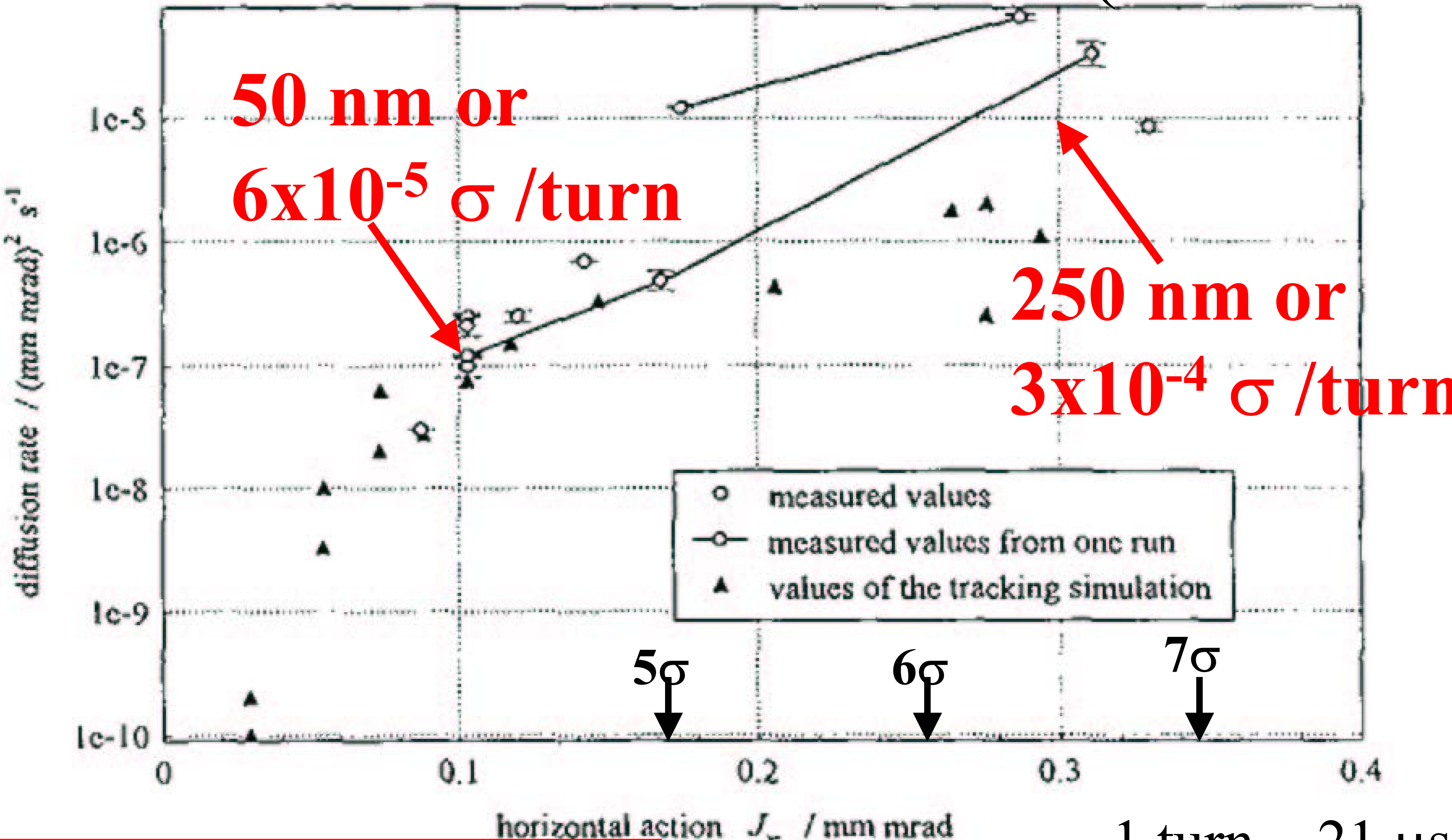
HERA
(M. Seidel, 1994)



same value for diffusion coefficient!

fits to background rate after scraper movement

HERA diffusion measurement (M. Seidel)

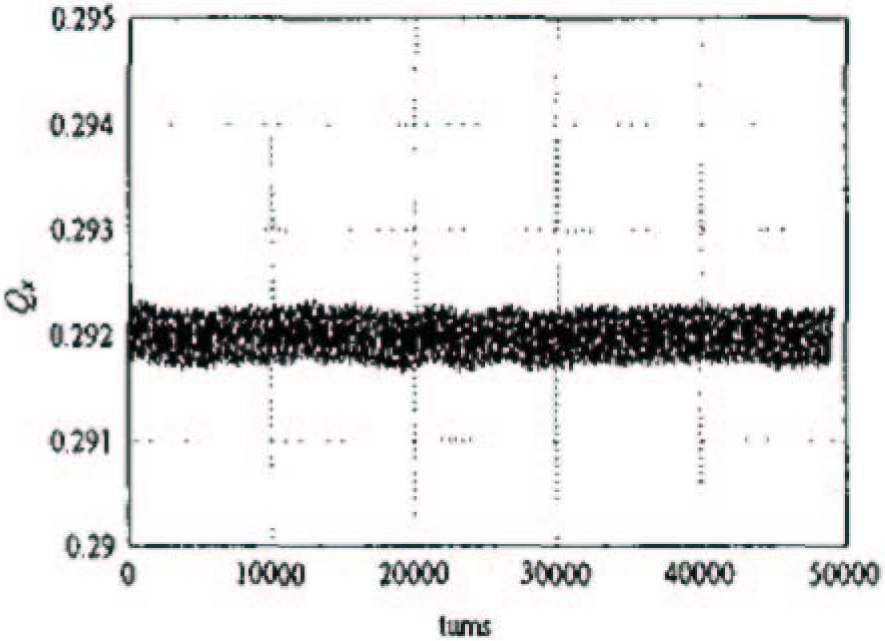


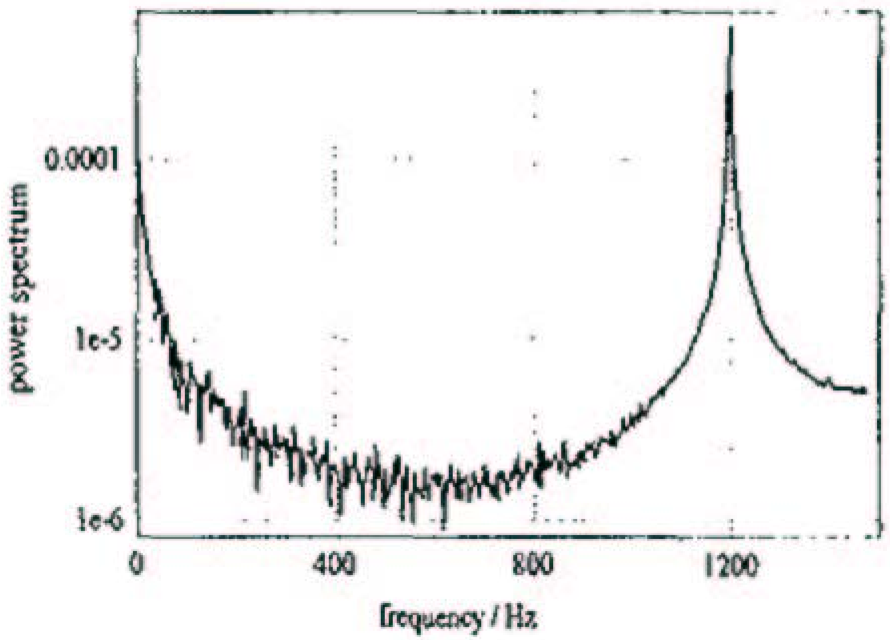
1 turn ~ 21 μs

$$\boxed{\frac{\partial}{\partial t} f(J,t) = \frac{1}{2}\frac{\partial}{\partial J} B(J) \frac{\partial}{\partial J} f(J,t)}$$

$B_x(J_x)$ [$\mu m^2 s^{-1}$] ~ a J_x^n with a~0.1, n~5

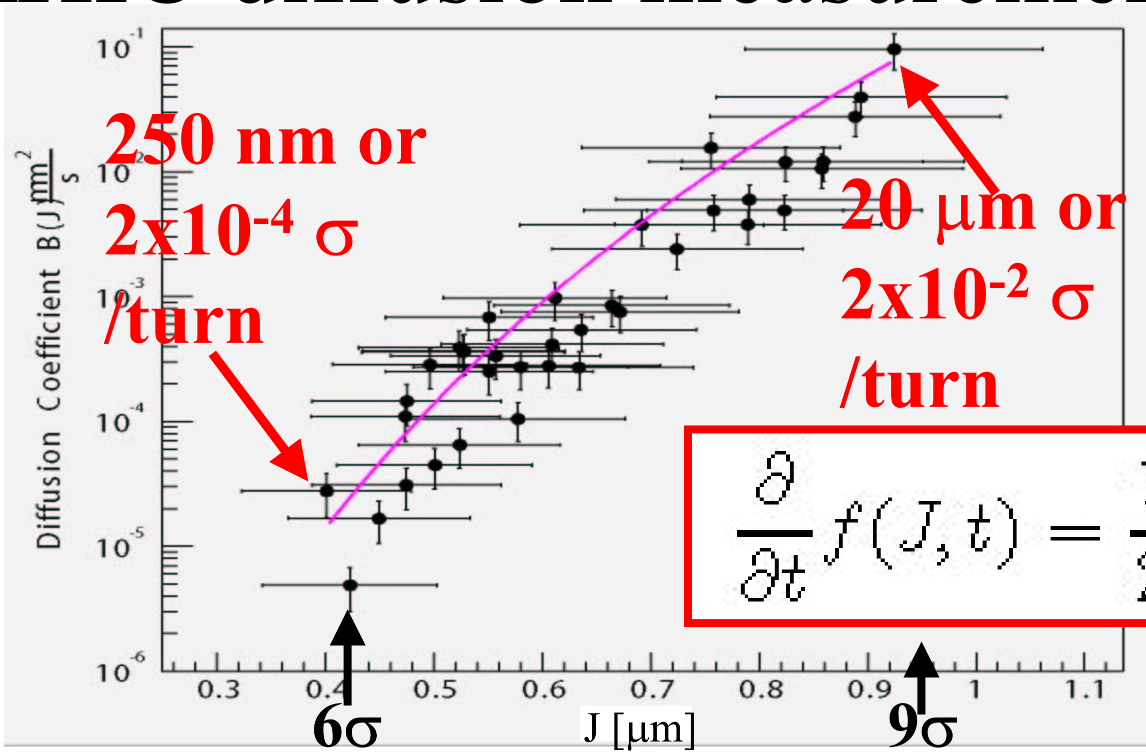
simple simulation can reproduce observed large-amplitude diffusion in HERA





tune evolution vs. time and power spectrum in M. Seidel's simulation, with a random drift of 5×10^{-5} (0.1 s correl. time), and a 2×10^{-4} harm. tune modulation at 1200 Hz

RHIC diffusion measurement (R. Fliller III)



fit loss rate after collimator insertion or retraction to diffusion equation:

$$\frac{\partial}{\partial t} f(J,t) = \frac{1}{2}\frac{\partial}{\partial J} B(J) \frac{\partial}{\partial J} f(J,t)$$

2002 data

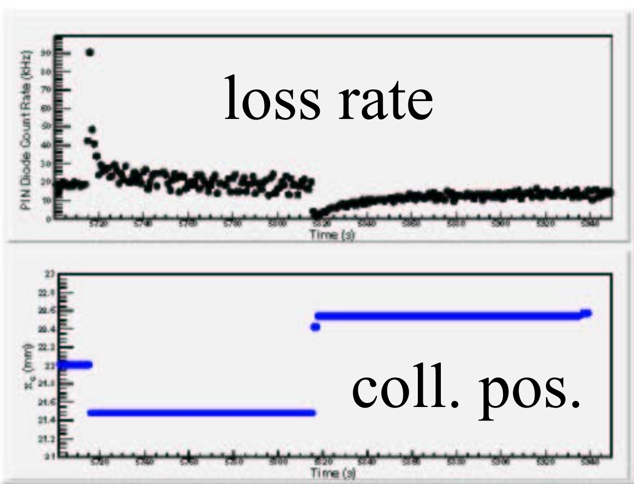
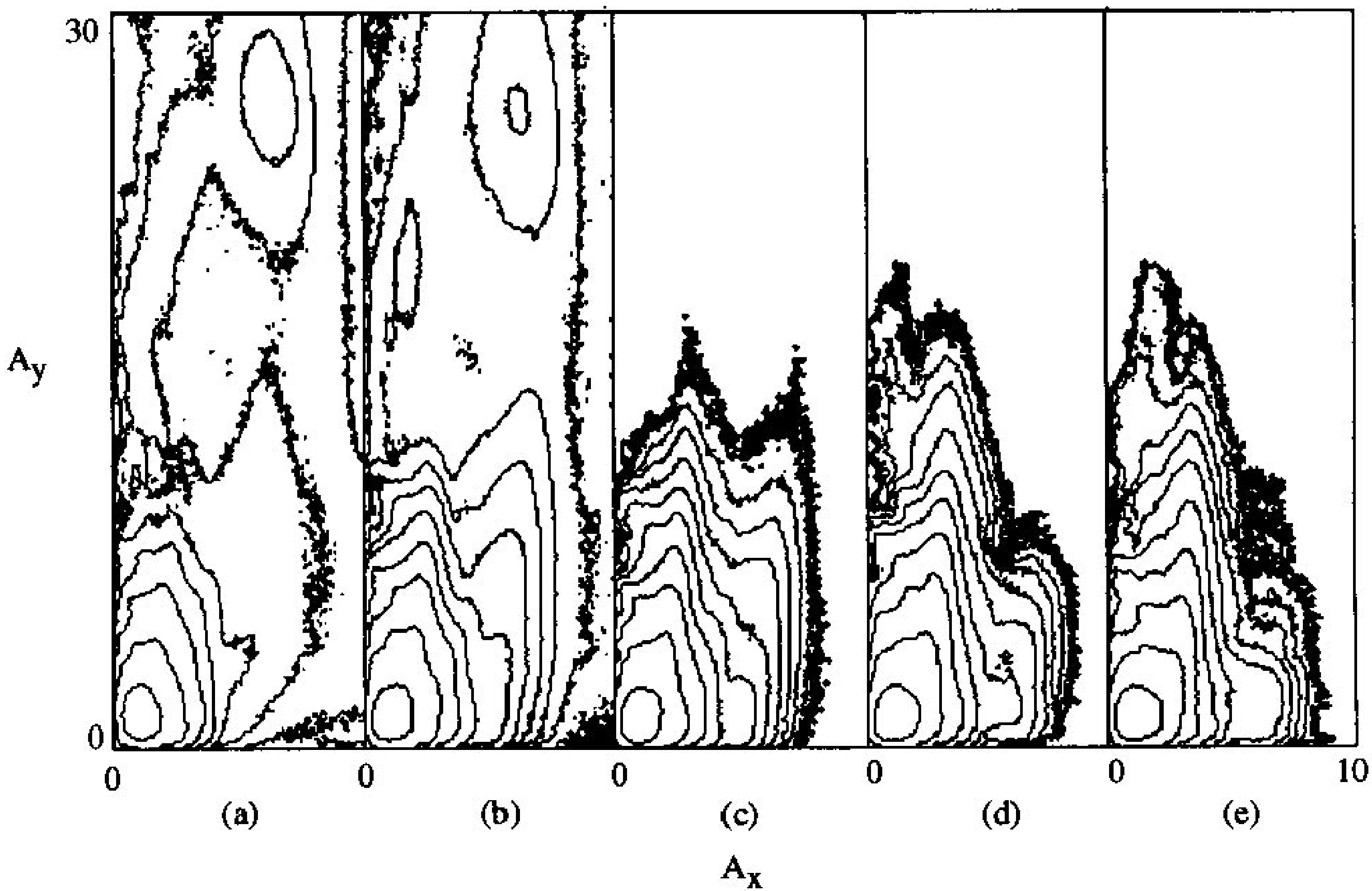


Table Results of Fit to $B(J) = bJ^n$

Store Number	b $\mu m^{2-n} s^{-1}$	n
01413	0.17 ± 0.09	10.3 ± 1.2
01874(i)	0.045 ± 0.026	8.5 ± 1.5
01924(i)	0.06 ± 0.02	7.0 ± 0.8
02136	7.8 ± 5.5	5.7 ± 0.6
02175	0.0036 ± 0.0005	3.0 ± 0.3

(i) indicates injection energy

(T. Chen, J. Irwin, R. Siemann, 1993)



tail distribution with parasitic separations:

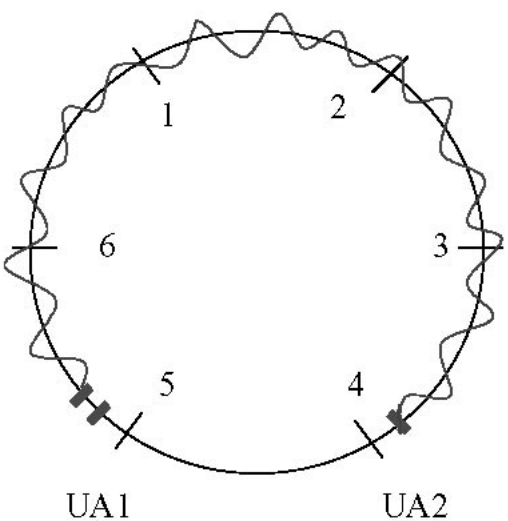
6.7 σ, 7.7 σ, 8.4 σ, 10.0 σ, 11.7 σ

hadron long-range (LR) collisions

- perturb motion at large betatron amplitudes, where particles come close to opposing beam
- cause 'diffusive aperture' (Irwin), high background, poor beam lifetime
- increasing problem for SPS, Tevatron, LHC,...

that is for operation with bunches

example

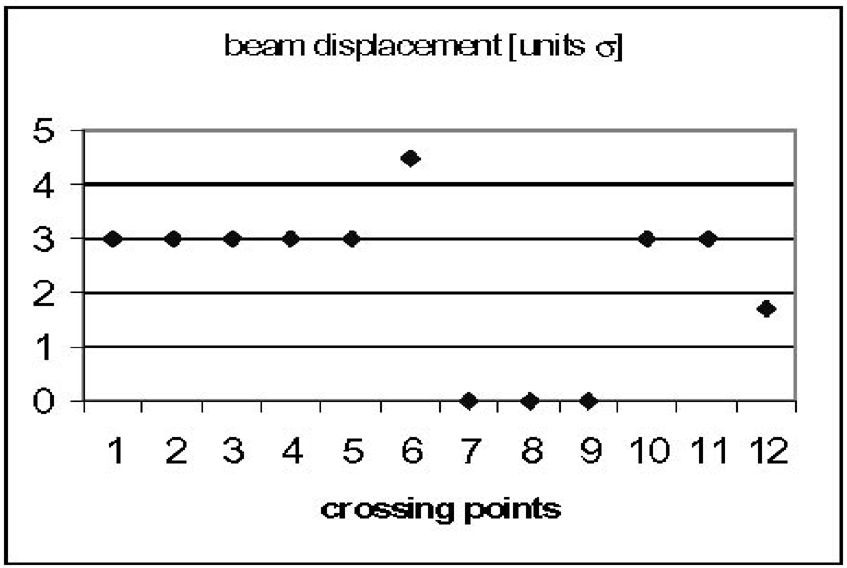


schematic layout of SPS pretzel scheme

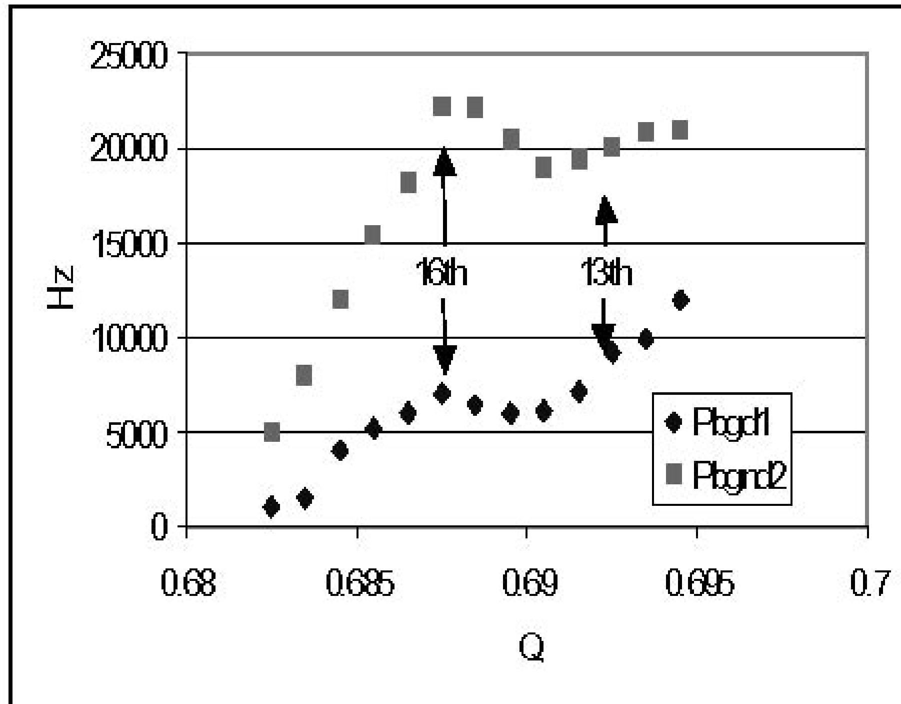
(Cornelis)

long-range collisions in SPS

nominal beam half separation in 12 SPS crossing points:

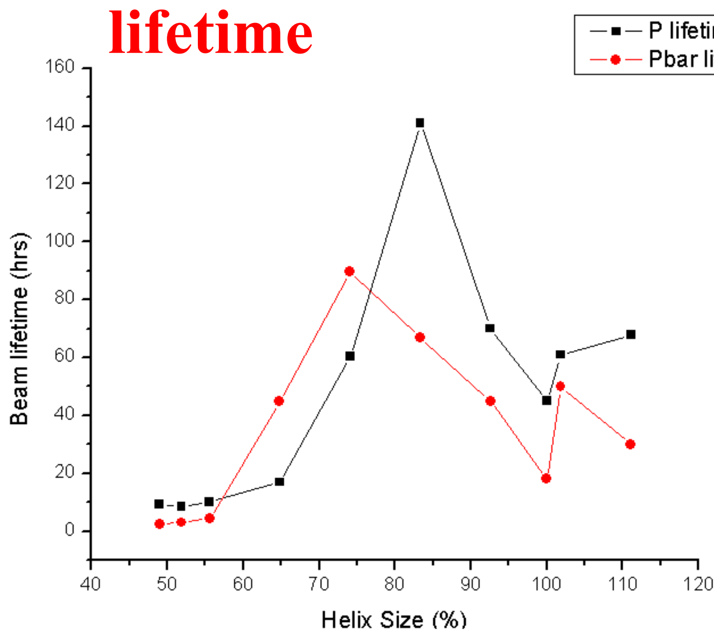


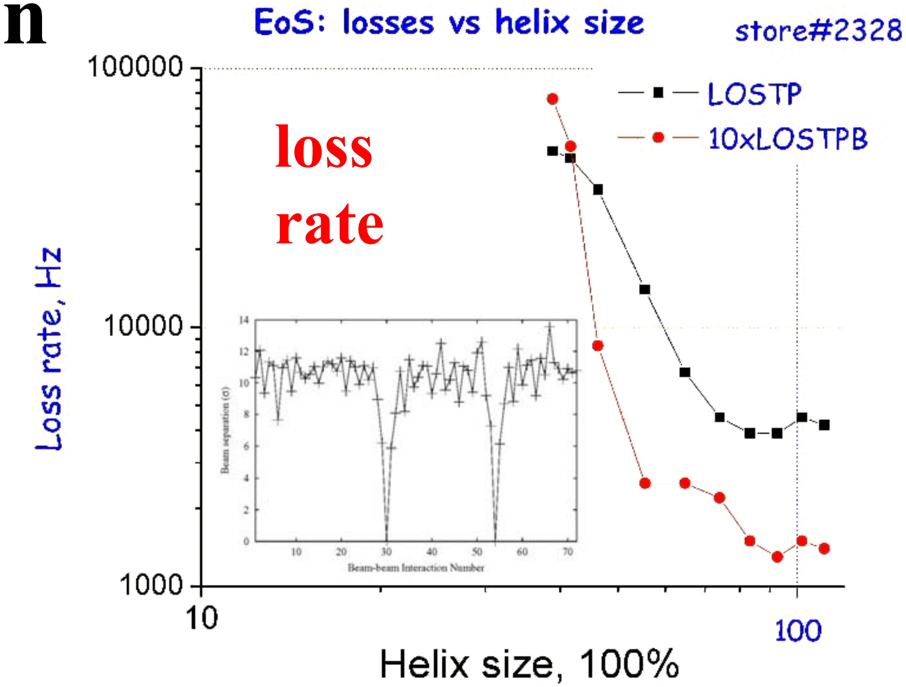
tune scans with full & ½ nominal separation

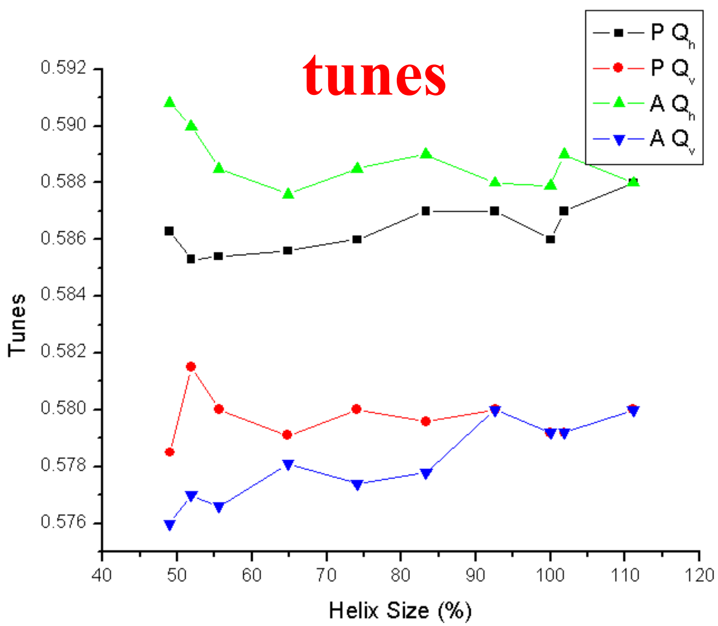


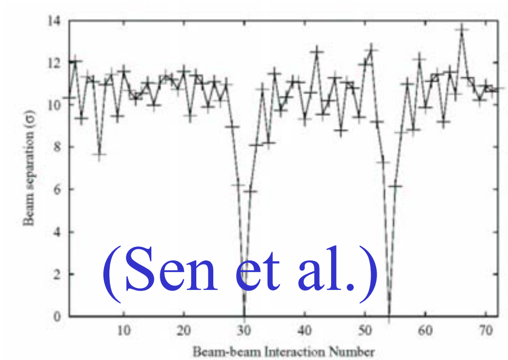
(Meddahi, Cornelis, et al)

LR separation in Tevatron

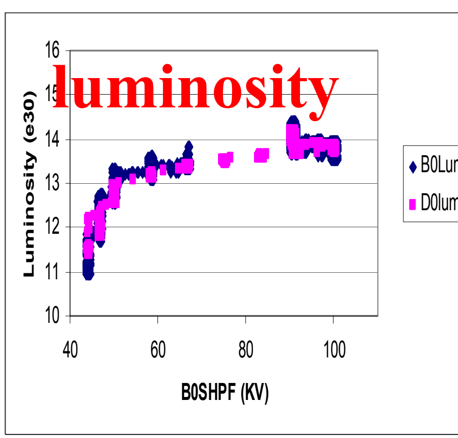






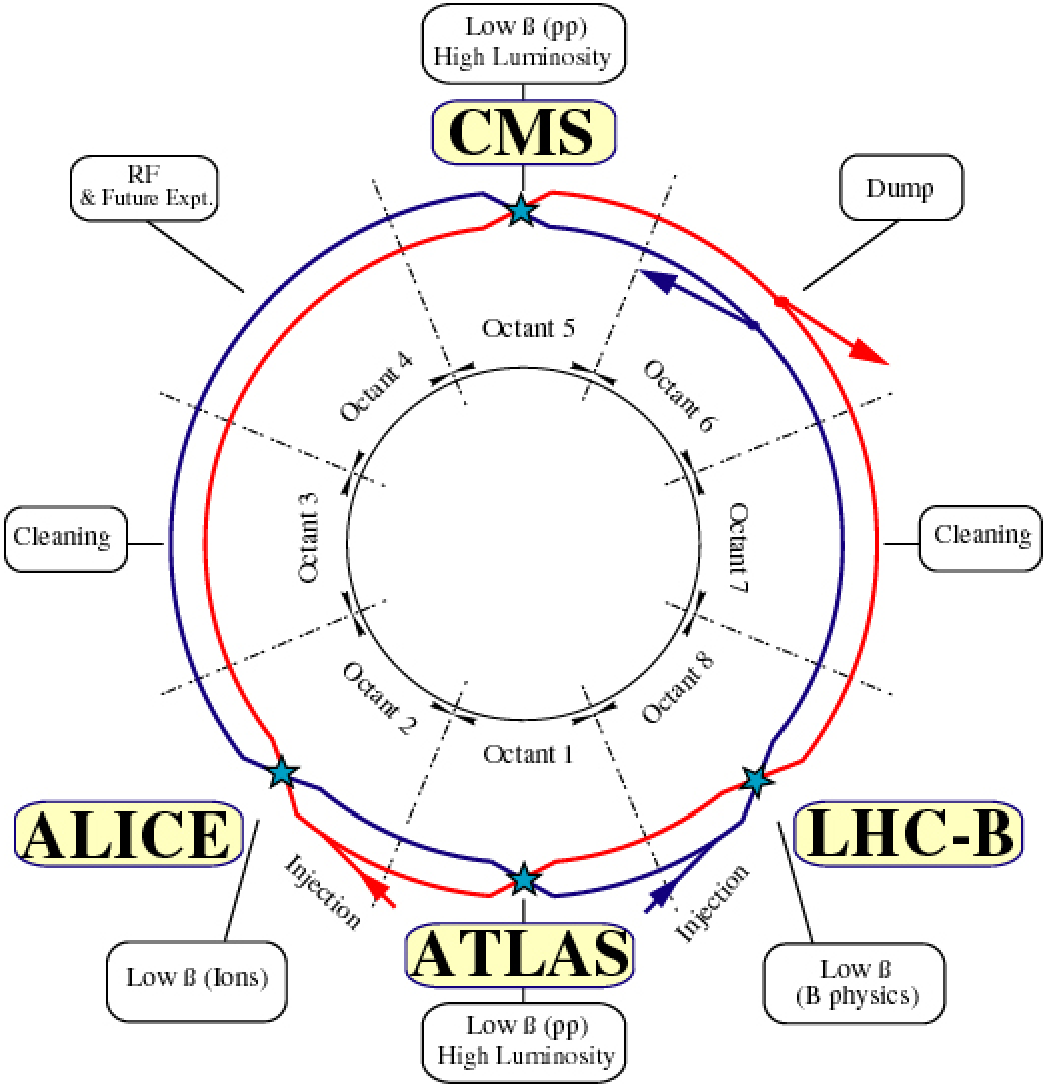


separations for bunch 6



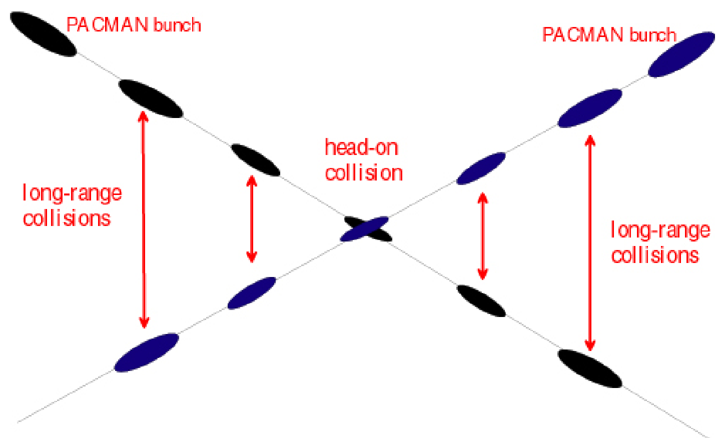
(X.-L. Zhang, 2003)

LHC: 4 primary IPs



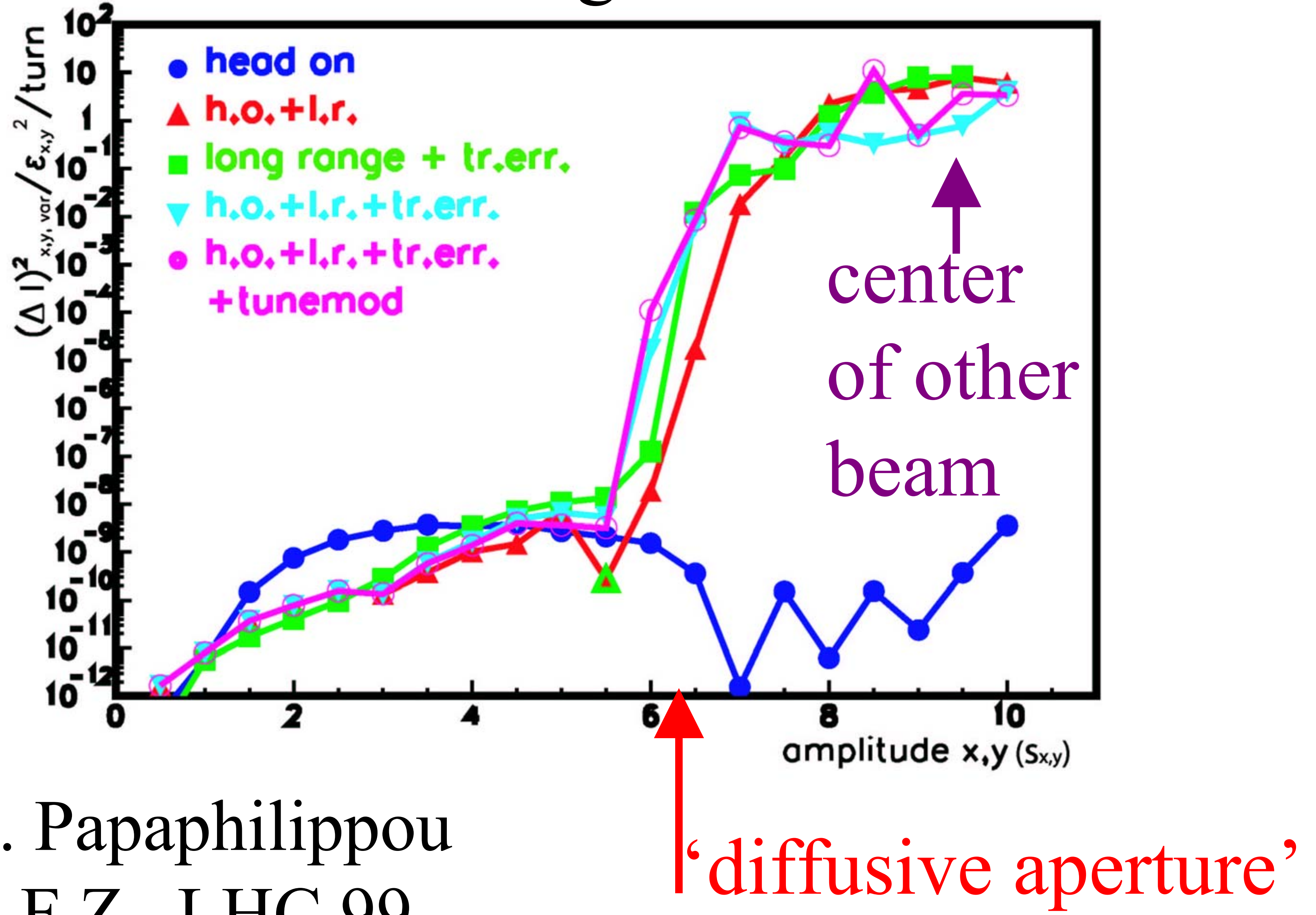
and

30 long-range collisions per IP



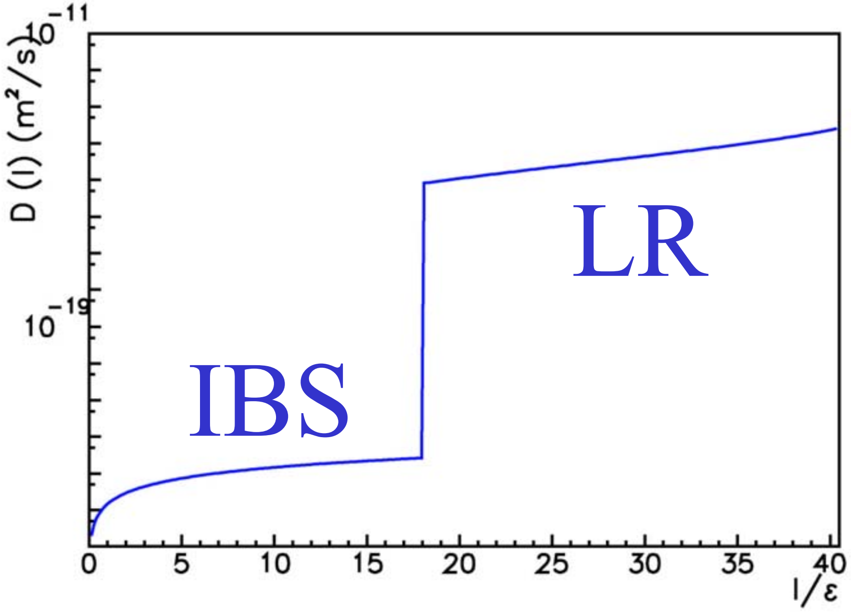
120 in total

result of weak-strong simulations for LHC



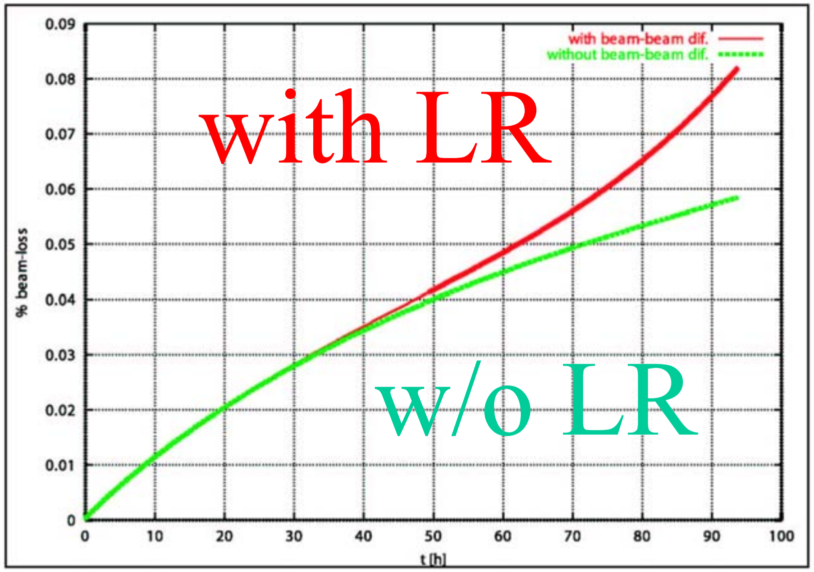
Y. Papaphilippou
& F.Z., LHC 99

model diffusion for LHC



proton loss vs time

0.09%



100 h

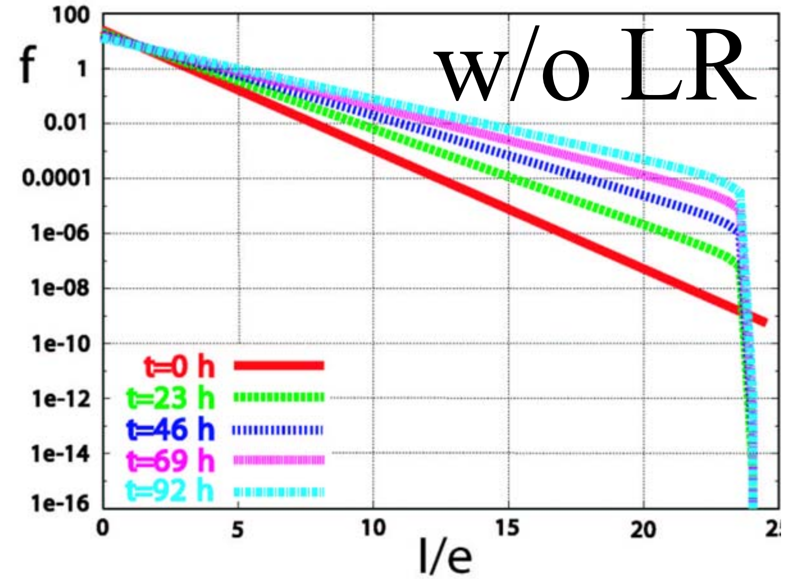
EPAC'2002

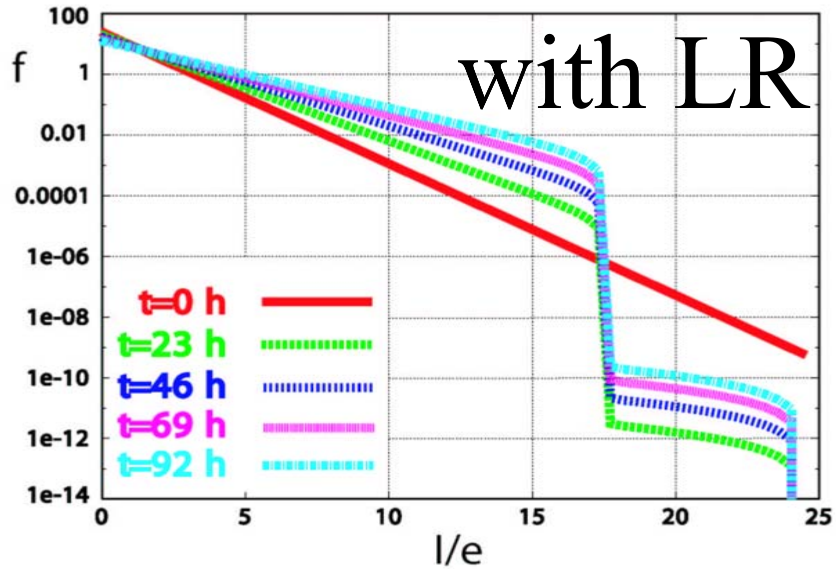
$$\boxed{D_{\mathrm{lr}}(I) \;=\; \frac{K^2 f_{\mathrm{rev}}}{2}\frac{1}{A-1}f(A)\,,}$$ where

$$f(A) \;=\; \left[A^3 - A^2 + 4A^2\sqrt{\tfrac{1-A}{1+A}} - 6A + 6 - 6\sqrt{\tfrac{1-A}{1+A}}\right],$$

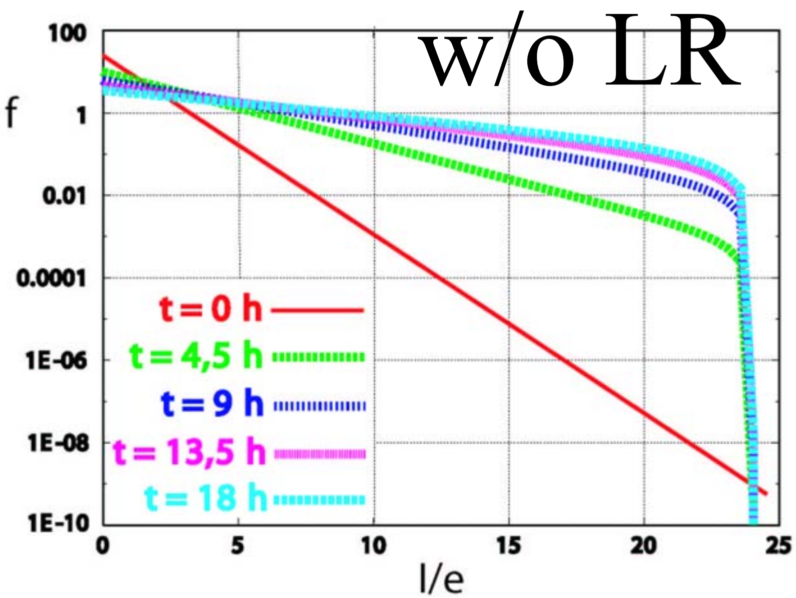
$A = \sqrt{2I/\beta^*}/\theta_c$, and $K = 2r_p N_b n_{\mathrm{par}}/\gamma$. For the LHC $\beta^* = 0.5$ m, $f_{\mathrm{rev}} = 11$ kHz (revolution frequency), $\theta_c = 300\mu$rad (crossing angle), $N_b = 1.1 \times 10^{11}$, $n_{\mathrm{par}} = 30$ (considering 1 IP), $r_p \approx 1.5 \times 10^{-18}$ m, $\gamma \approx 7461$.

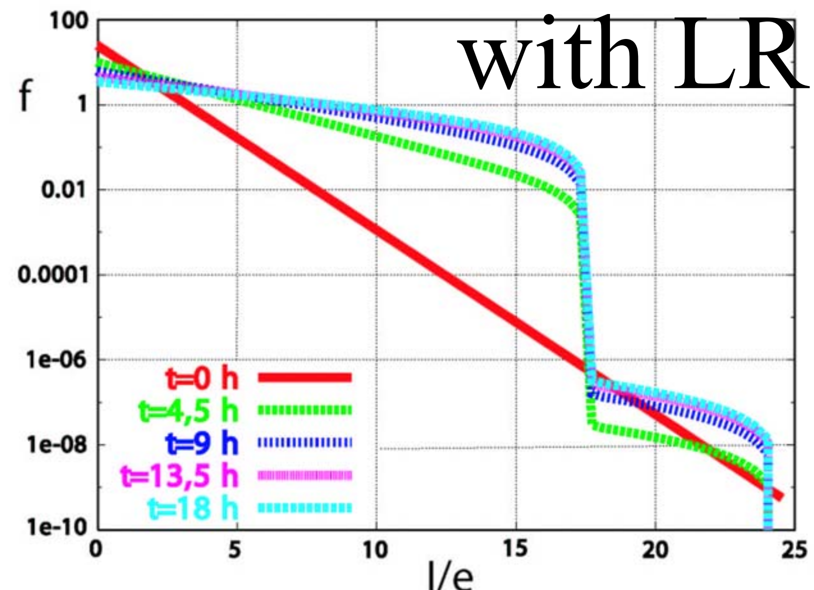
analytical expression for LR diffusion (Y. Papaphilippou & F.Z., PRST-AB 074001)





IBS only





30x larger core dif-fusion

LHC density distribution at various times

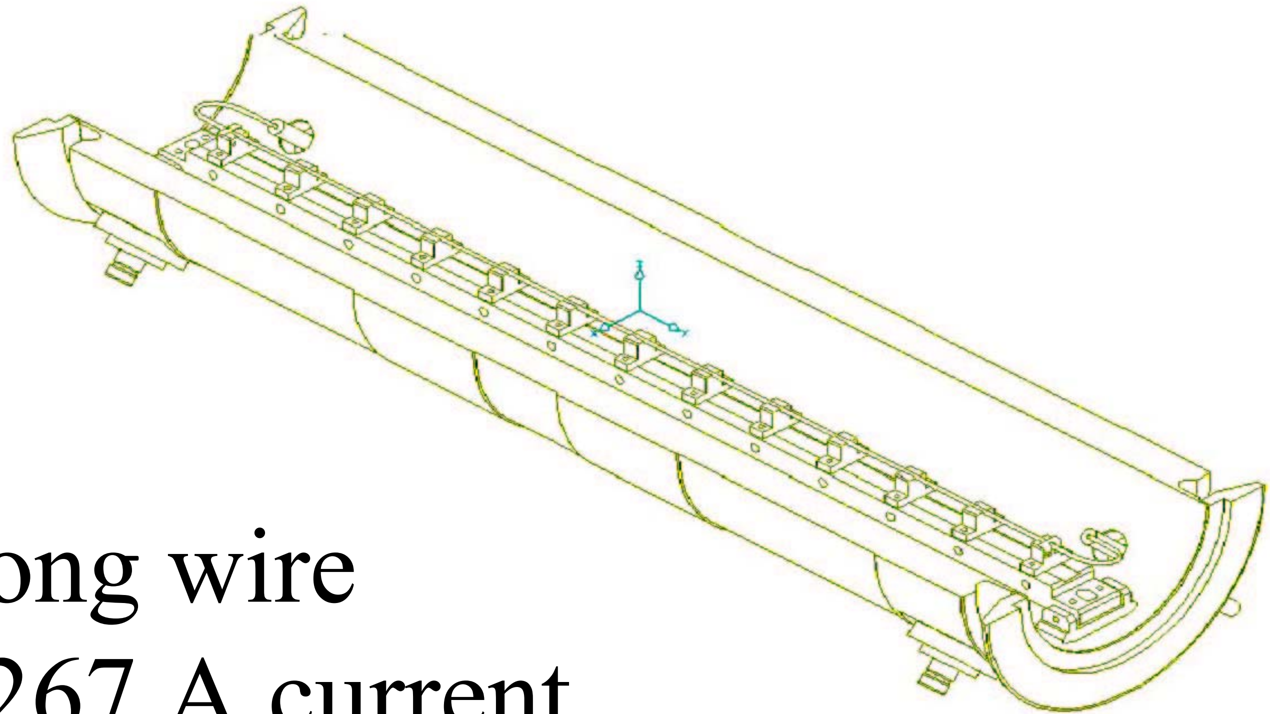
(M.-P. Zorzano, 2002)

Study of LHC LR Effect in SPS

J.P. Koutchouk, G. de Rijk, J. Wenninger, F. Zimmermann

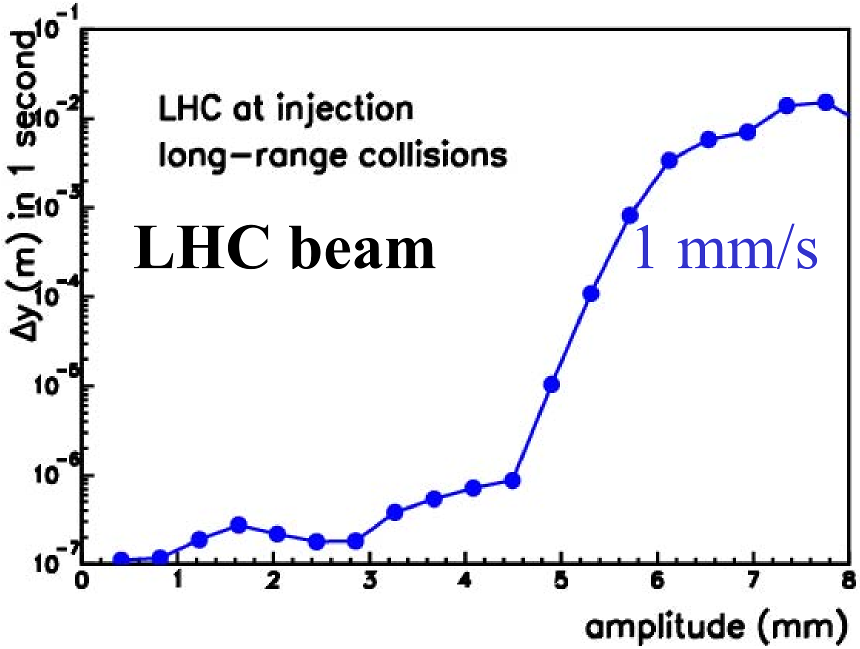
Tech. Coord.
J. Camas/BI

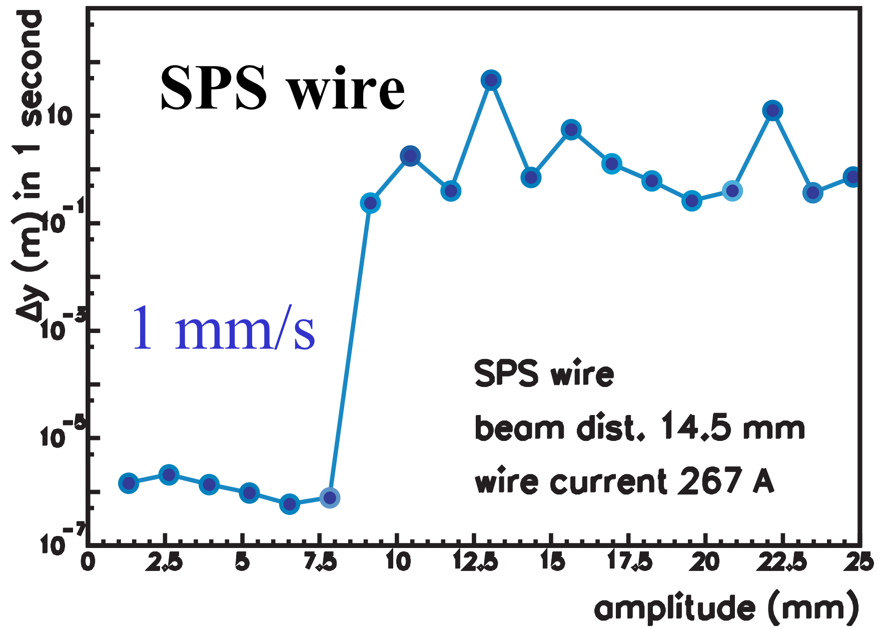
Help from
many groups



1 m long wire
with 267 A current

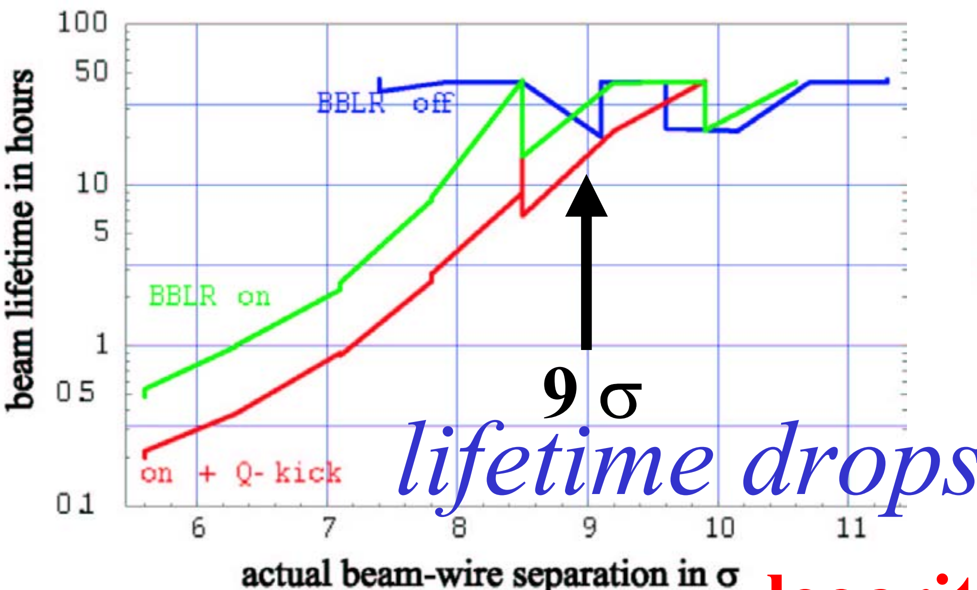
LHC long-range collisions will cause a fast particle loss at large amplitudes

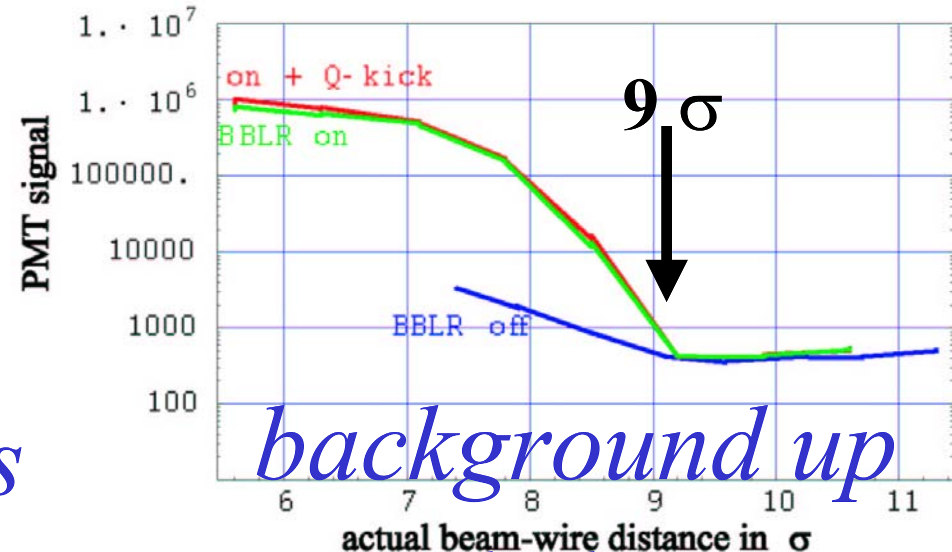




effect of 1-m long wire at 9.5σ from beam center, carrying 267 A current, resembles the total number of long-range collisions in the LHC

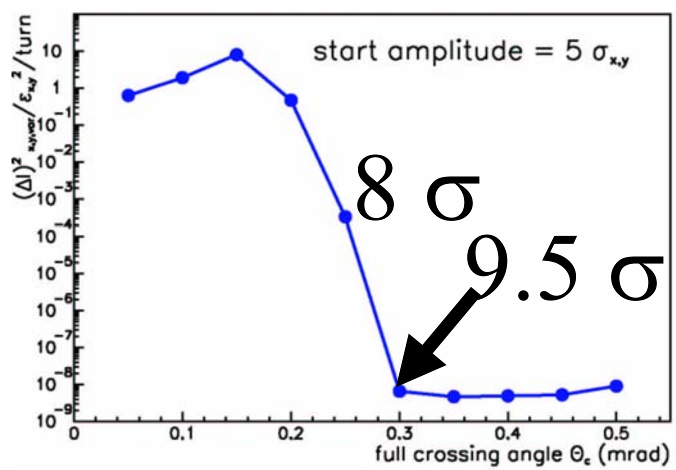
preliminary evidence for diffusion vs. beam-wire distance in SPS





logarithmic scales! *below 9σ!*

compare with LHC simulation:



tail recipes

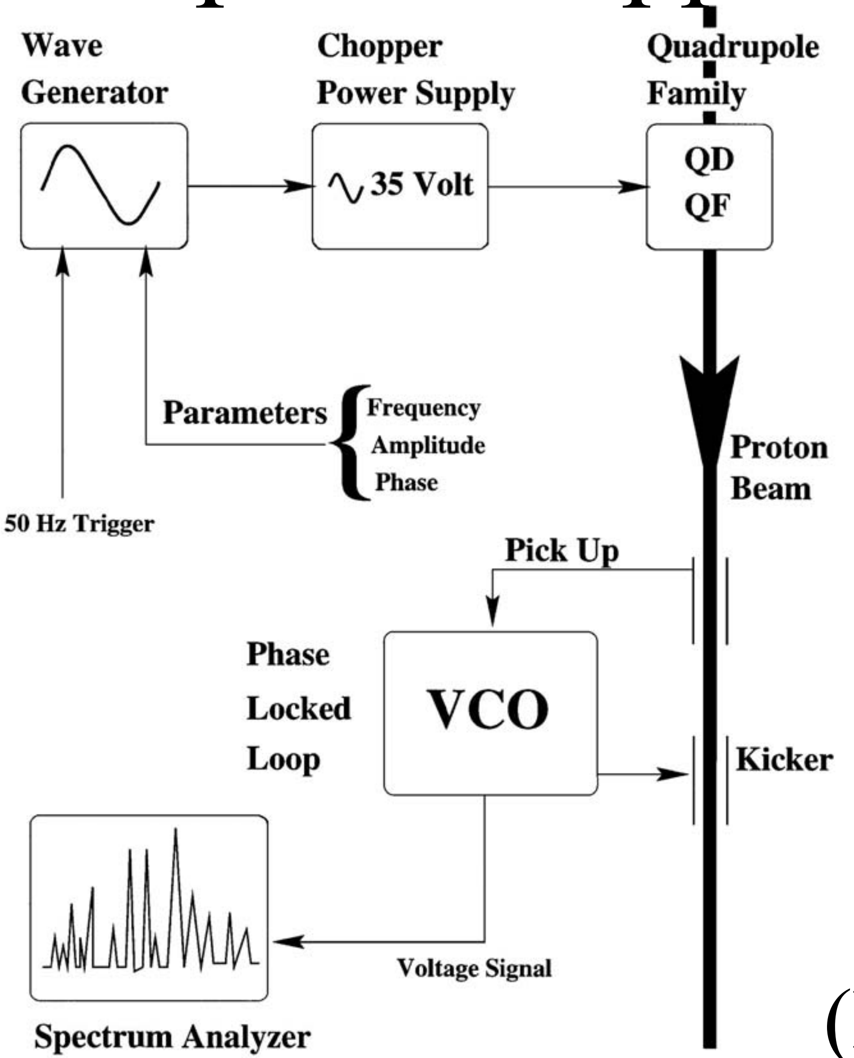
- match beam sizes, center collisions, zero crossing angle, optimize tunes

blue: established

- octupoles, or other nonlinear elements, to vary resonance parameters at large amplitudes
- if possible introduce self-compensation, e.g., x and y crossing at different IPs, or cancellations between central and long-range collisions
- quadrupole wiggler for leptons
- (optical) stochastic or electron cooling for hadron??
- suppress tune modulation by active filters on power supplies or by tune-modulation feedback on the beam
- long-range beam-beam compensator
- electron lens??

red: under study

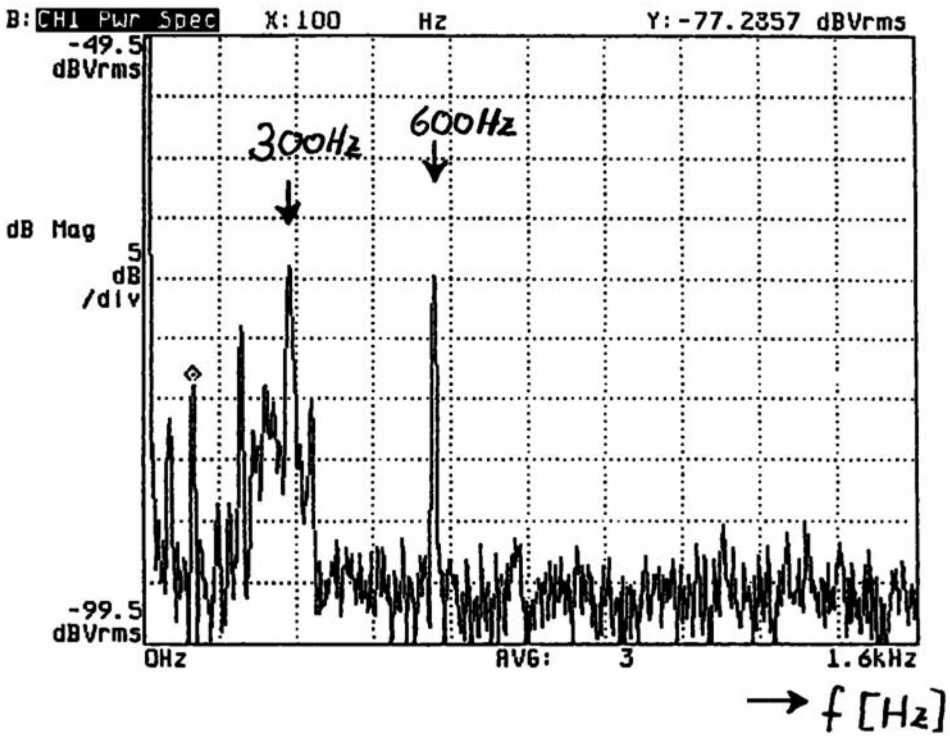
compensating tune ripple due to power supplies (in HERA)

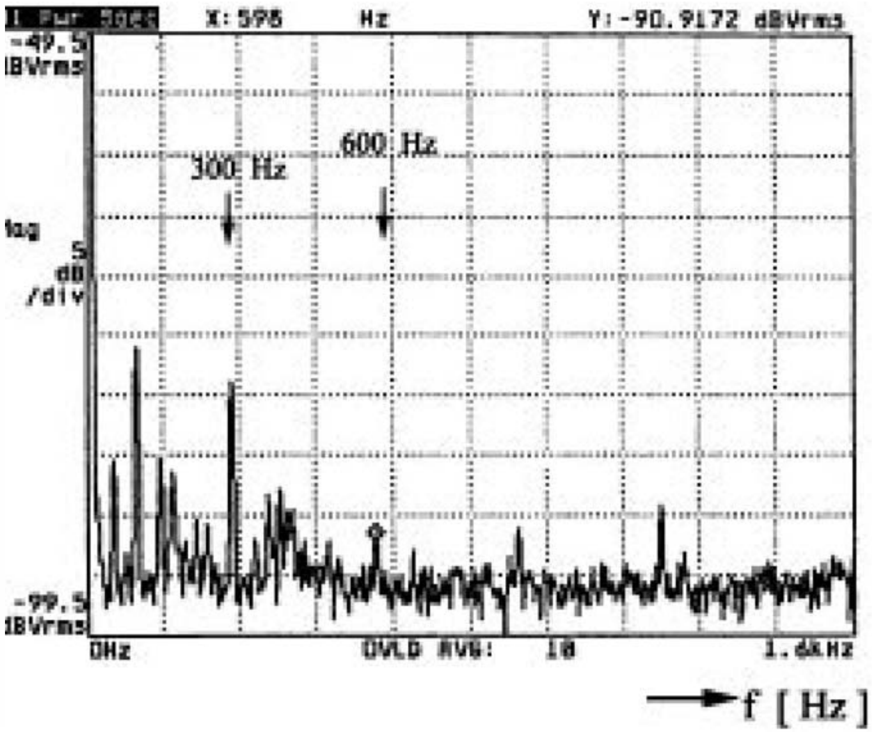


excite additional modulation locked to power supply frequency

tune monitor which can measure 10^{-5} modulation depths

(Bruning, Willeke, 1996)



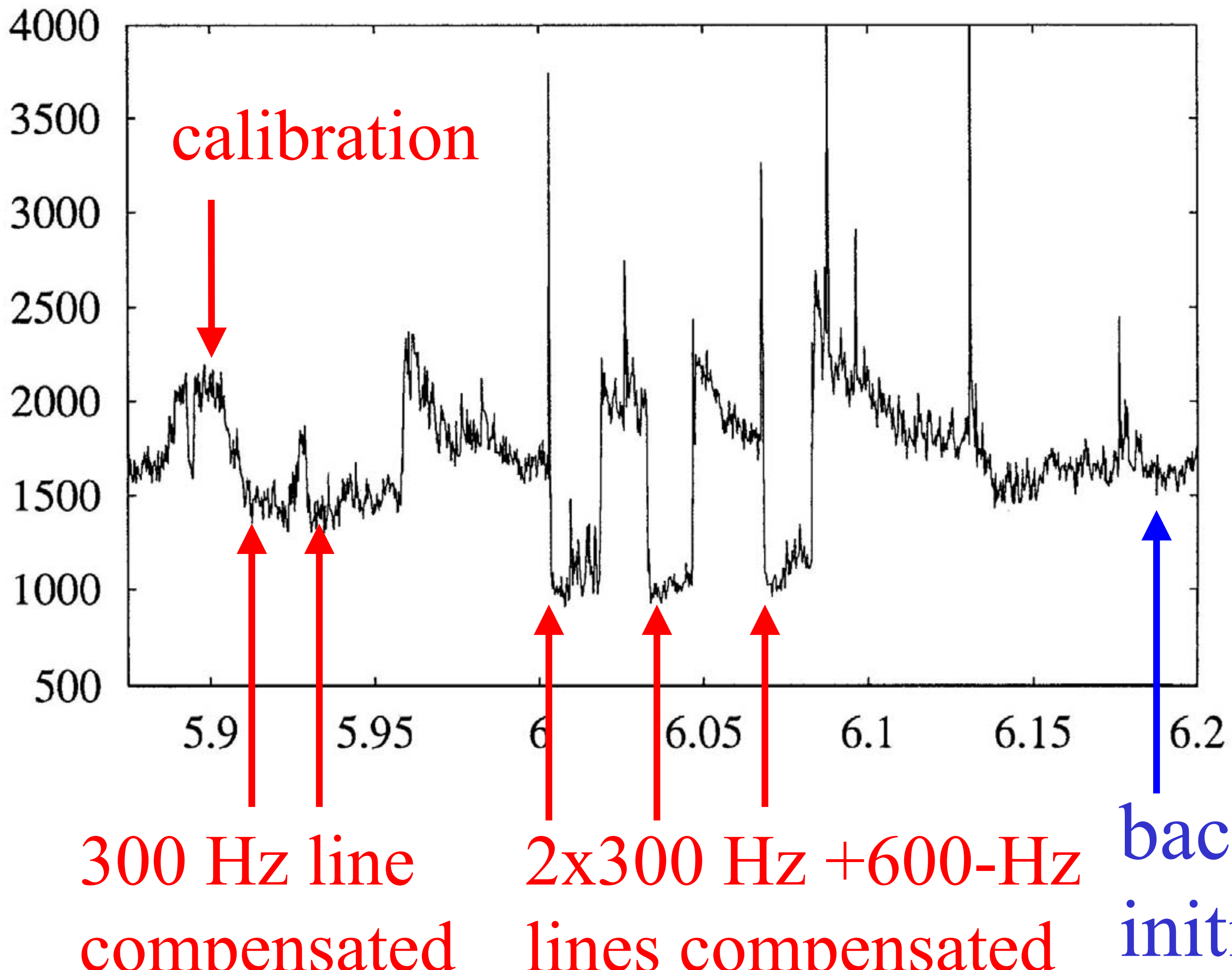


calibration with addt'l modulation at 620 Hz

compensation of 600 Hz line by addt'l mod. of 8×10^{-5}

(Bruning, Willeke, 1996)

proton loss rate reduced by ~40%! (but it grows when compensation is switched off, - due to core diffusion?)



(Bruning, Willeke, 1996)

VEPP-4/-2M & DAΦNE use(d) <u>octupoles</u> to control tails; they have two effects:

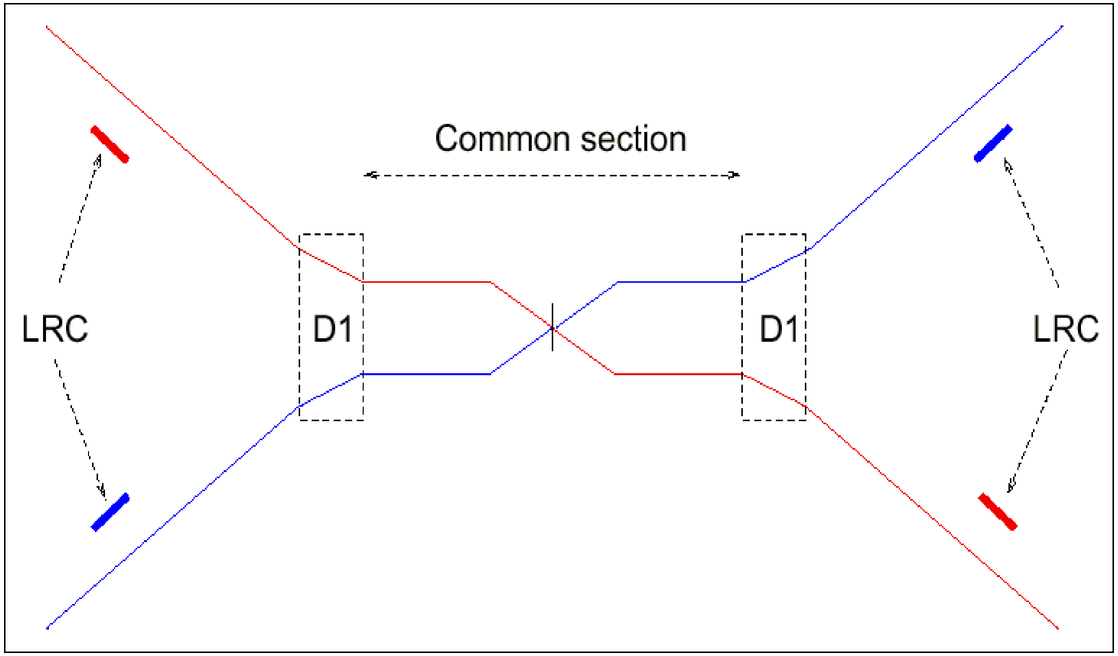
- compensate or increase tune footprint
- widen or reduce resonance width and 'fold' the detuning with amplitude; reduces or enhances decoherence of coherent oscillations

which of the contradicting effects prevails was decided experimentally

(A. Temnykh, M. Zobov)

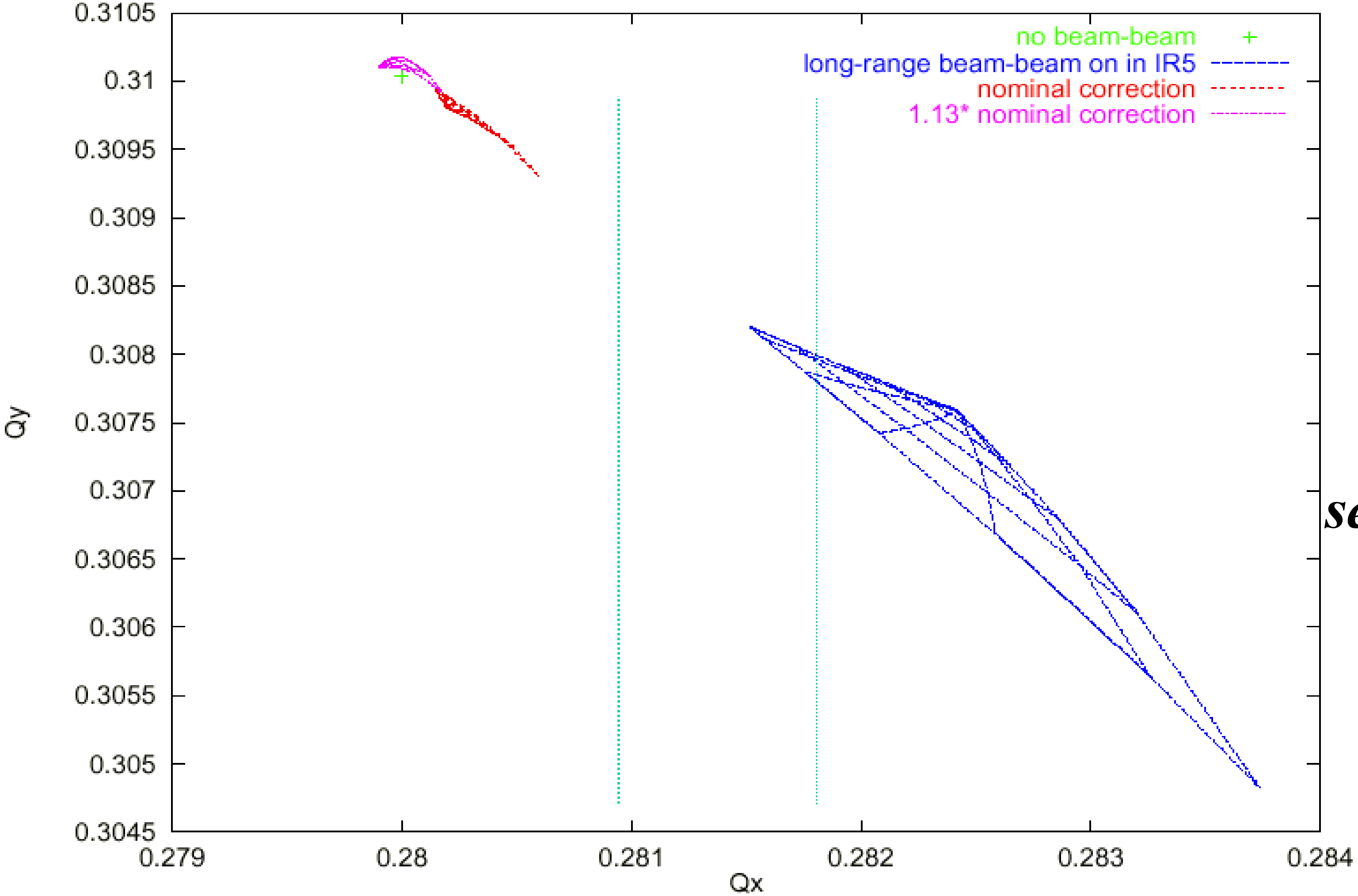
Long-Range Beam-Beam Compensation for the LHC

- To correct **all** non-linear effects correction must be **<u>local</u>**.
- Layout: 41 m upstream of D2, both sides of IP1/IP5



(Jean-Pierre Koutchouk)

simulated LHC tune footprint with & w/o correction



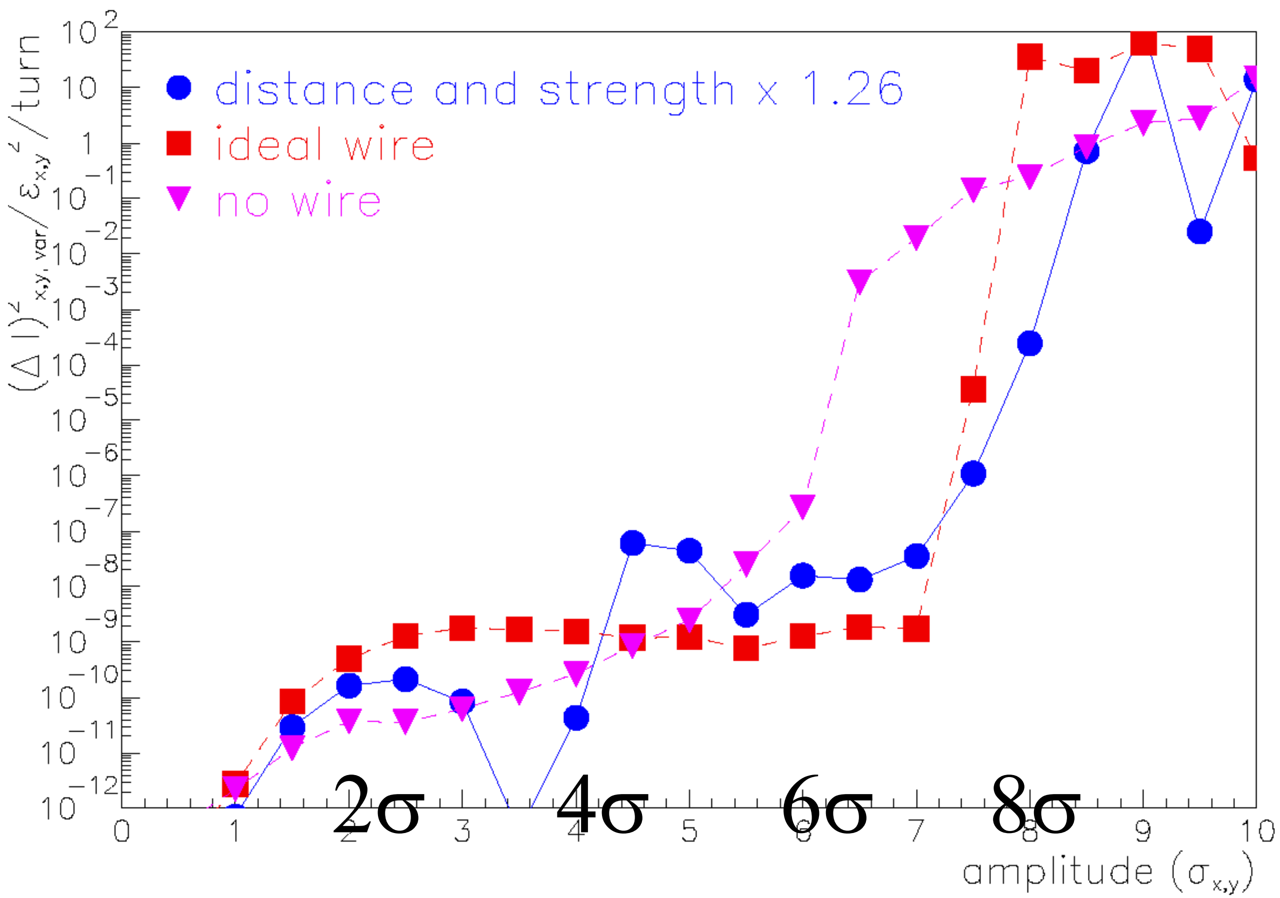
- .16σ
- .005σ
- .016σ

Beam separation at IP

(Jean-Pierre Koutchouk)

LHC diffusion rate in weak-strong simulation; compensation increases ‘diffusive aperture’ by ~1or 2σ

local diffu-sion rate



amplitude

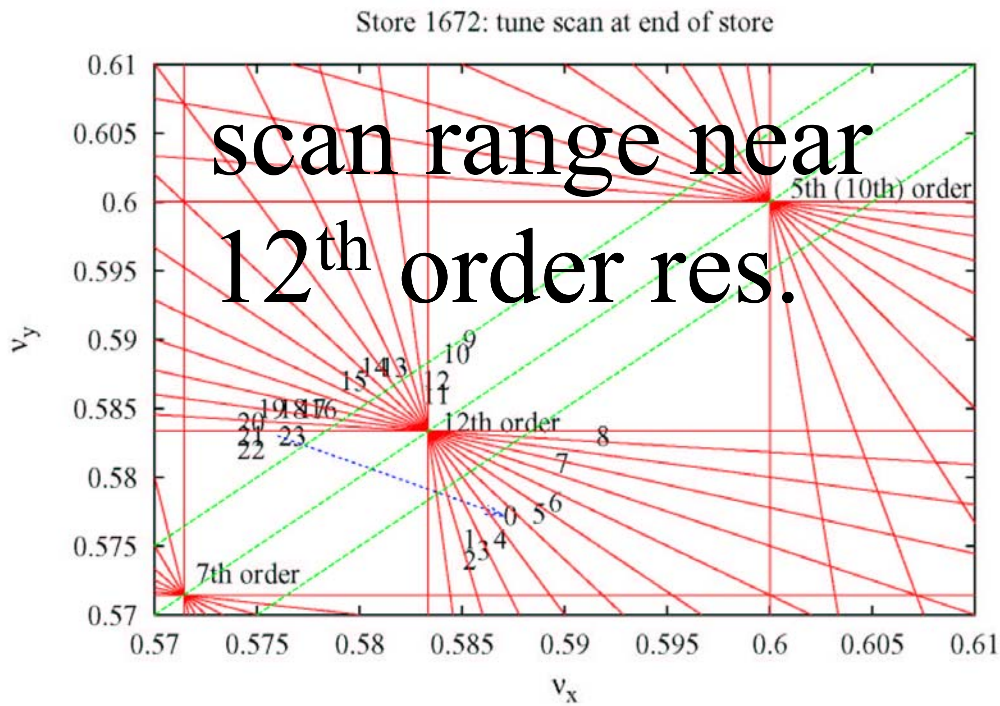
conclusions

- impressive simulations with high predictive power for lepton colliders (though a few discrepancies remain between codes)
- for hadrons: diffusion rates in HERA and RHIC extremely similar; Tevatron Run-II and LHC enter new regime where LR collisions are dominant; the latter cause fast losses and may ensure that no tails develop (!)
- possibly new & surprising incoherent effects
- various means to manipulate tails, e.g., octupoles, electron lens, LHC LR compensator

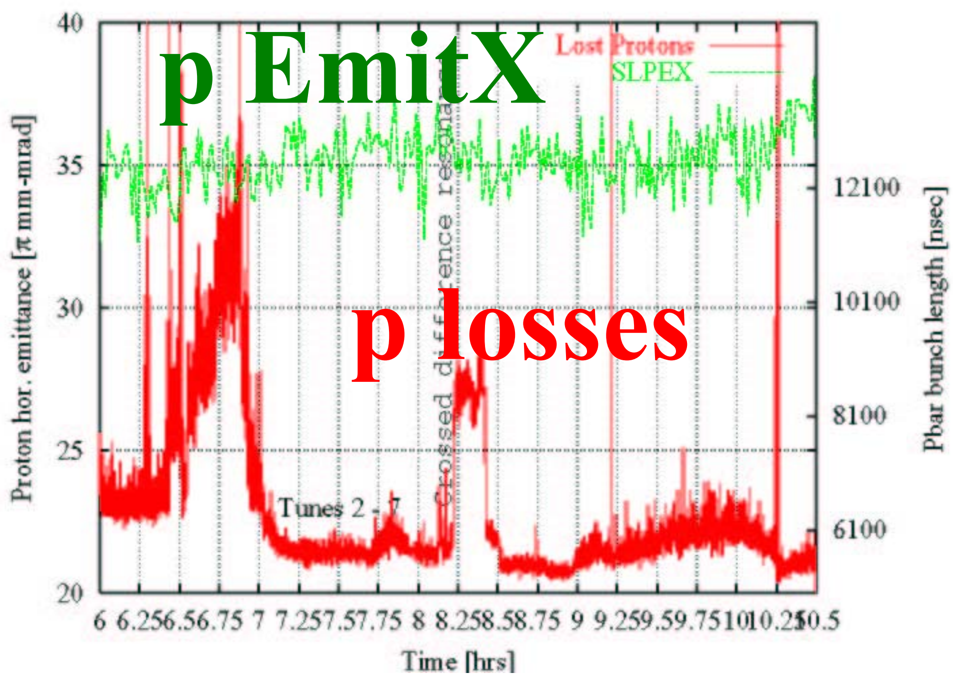
Thanks!

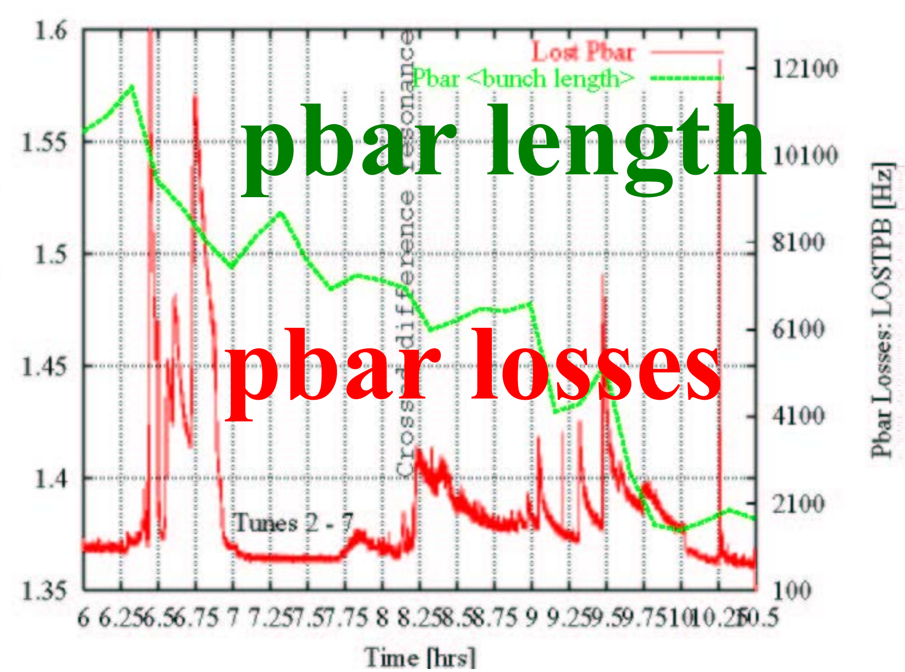
- **W. Fischer, R.P. Fliller**, A. Drees, S. Peggs, BNL
- **T. Sen, X.-L. Zhang, V. Shiltsev**, FNAL
- **M. Zobov**, INFN
- **M. Minty, M. Seidel**, F. Willeke, DESY
- **K. Ohmi, Y. Funakoshi,** KEK
- Y. Cai, SLAC
- **H. Burkhardt, J-P. Koutchouk, J. Jowett**, R. Assmann, F. Schmidt, CERN
- **M.-P. Zorzano,** INTA
- **Y. Papaphilippou,** ESRF
- **I. Reichel**, M. Furman, LBNL
- T. Chen, Teledyne

p & pbar loss rates vs tune in **Tevatron** (T. Sen)



no obviously better tunes;
emittance exchange on coupling resonance only with pbars
(beam-beam driven coupling)





Observables & Diagnostics

- Beam lifetime
- Beam profiles (flying wires, SL)
- Tunes & tune shifts
- Luminosity
- Loss rates & background
- Schottky power
- Collimator retraction, diffusion rates
- Vernier scans of offset and angle
- Helix size

Interplay with other phenomena

- gas scattering
- incoherent collision effects
- Touschek scattering, intrabeam scattering
- rf noise
- ground motion
- synchrotron radiation
- tune modulation
- lattice nonlinearities
- Impedances & collective effects

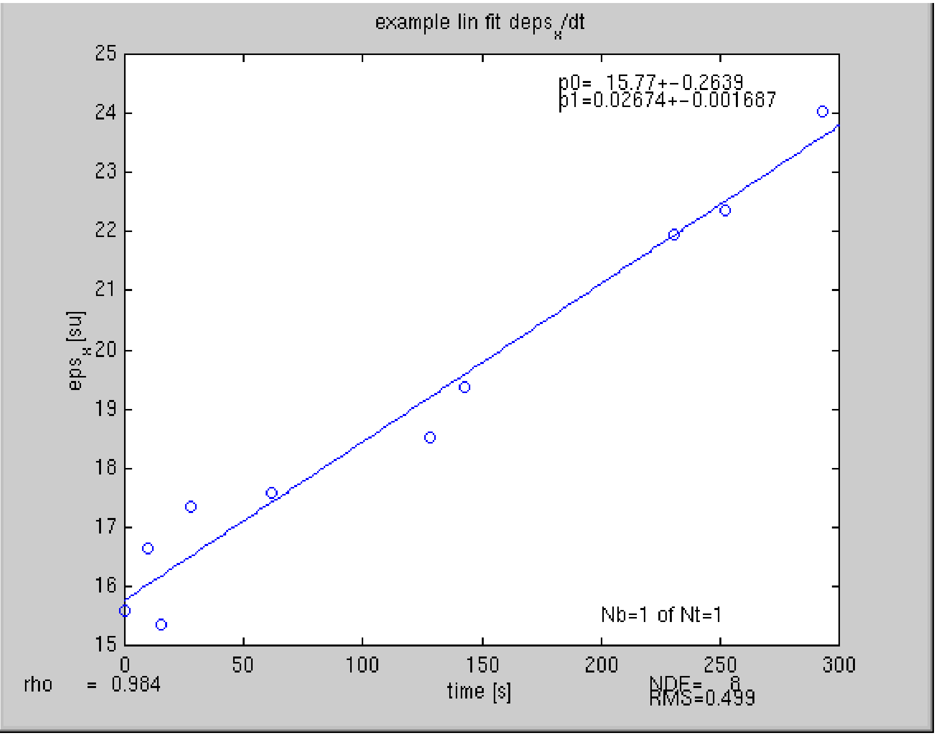
ISR – the first hadron collider

Parameter table

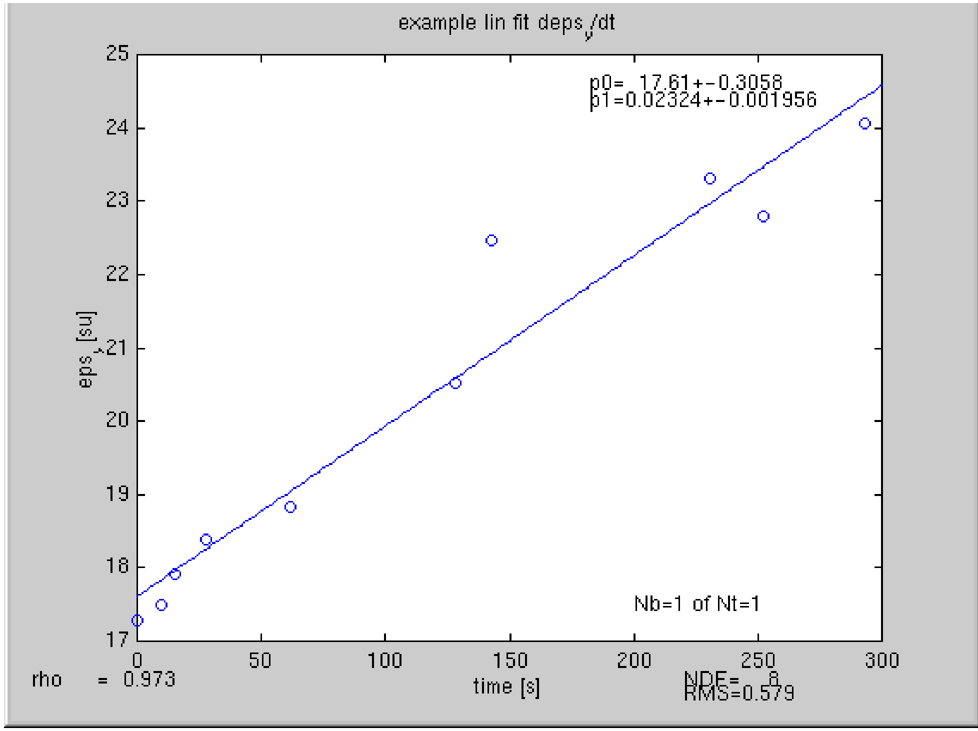
- Beambeam tune shift
- Special features (crossing angle, long-range etc.)
- species

proton emittance growth rate measured in HERA (2003)

x



y



	$\Delta\varepsilon_x/\Delta t$	$\Delta\varepsilon_y/\Delta t$
colliding bunches (all)	1.47 +/- 0.60	1.47 +/- 0.65
noncolliding bunches	0.36 +/- 0.07	0.34 +/- 0.05

units: 10^{-9} m-rad / hour (2 ♦, unnormalized emittance)

HERA

(M. Minty)

LEP – highest-energy e^+e^-

- incoherent scattering by beam-beam bremsstrahlung was responsible for vertical beam-beam tails

Variants and complications

- Crossing angle
- Long-range collisions
- Offsets and tilts at IP
- Spurious dispersion
- Longitudinal timing
- Strong-strong dynamics

KEKB – record ☹ factory

- no data on beam-beam tail
- particle physicists operate the collimators ("movable mask"), no systematic study
- simulations of beam-beam tail by K. Hirata, and later K .Ohmi et al.
- beam-beam tails are not a serious problem for KEKB, except during early commissioning
- if beam lifetime is reduced, also beam-core blow up is observed at the same time

(Y. Funakoshi, K. Ohmi)

Tevatron – highest energy p-pbar

- long-range collisions important; beam-distance controlled by size of "helix"
- "scallops" develop in both p and pbar beams
- extensive proton losses in the beginning of stores
- p/pbar losses vs helix size at low-beta (recent experiment by XiaoLong Zhang)
- tune scans at the EoS (X.-L. Zhang, T. Sen and M. Xiao)
- halo, losses, beam-beam – strong tune dependence!

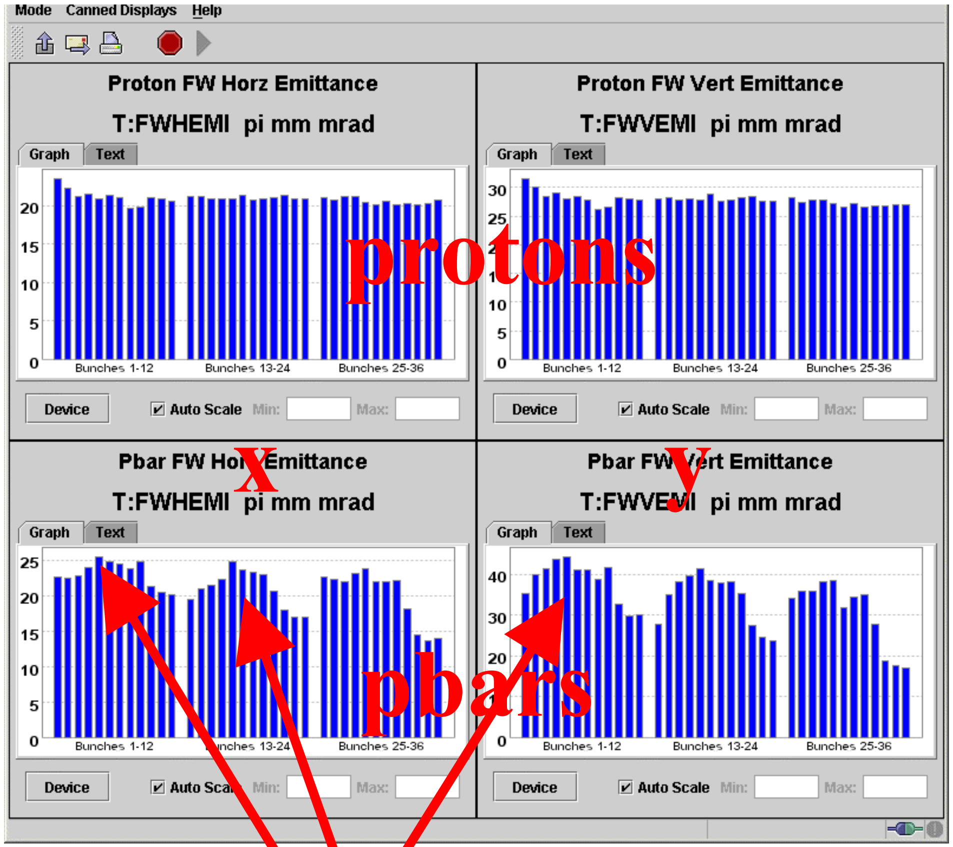
(T. Sen, V. Shiltsev, X.-L. Zhang)

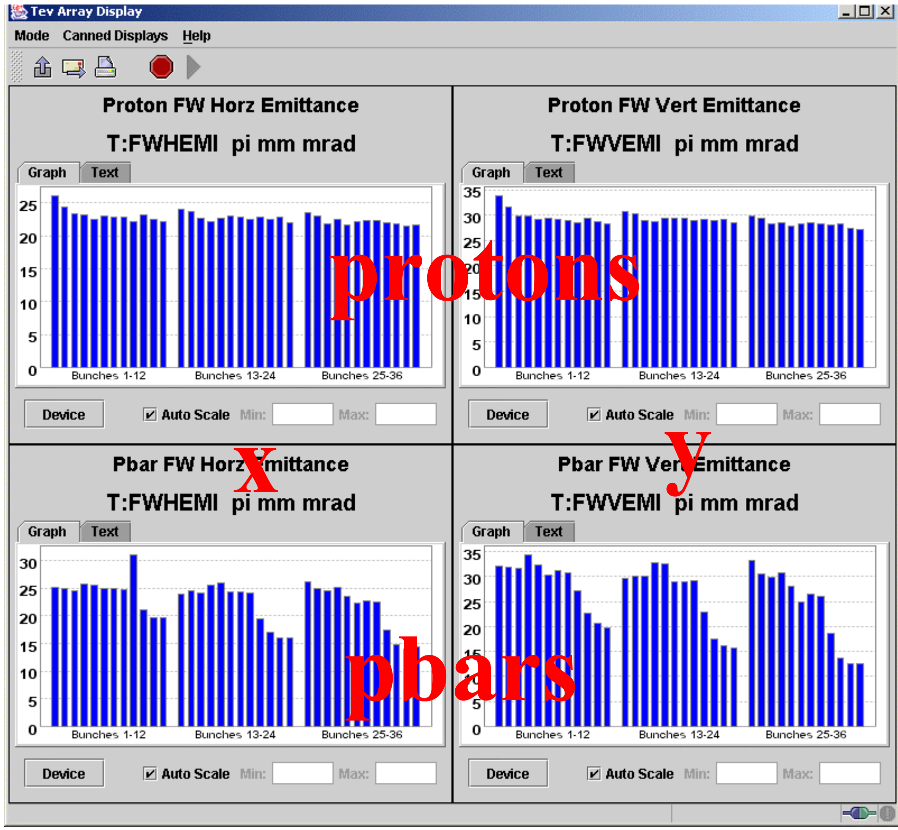
SPS – the first p-pbar collider

'Scallops' Tevatron (T. Sen)

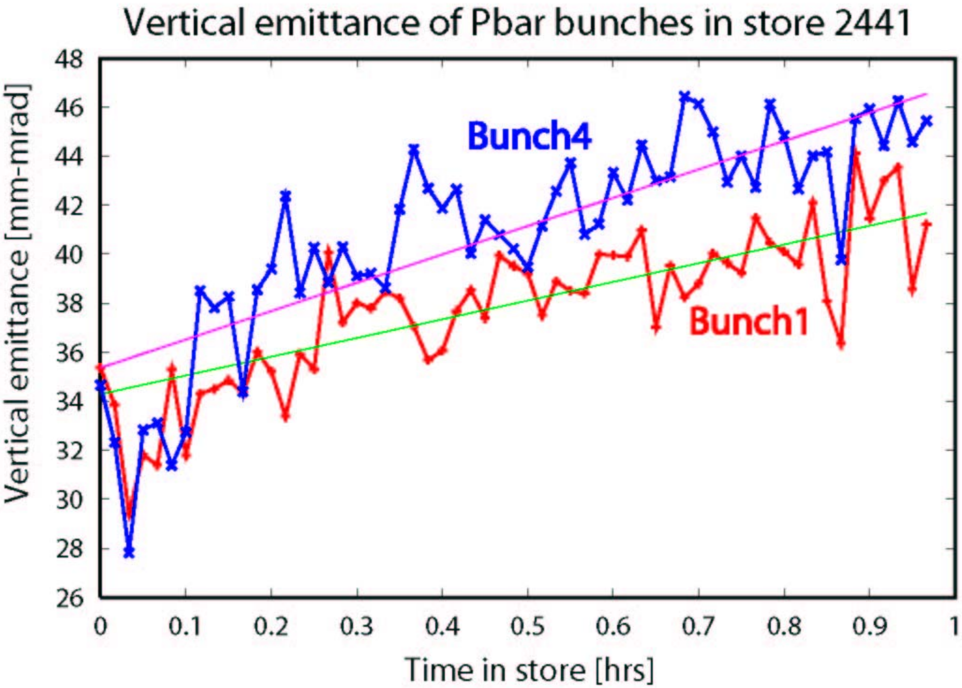
flying wire emittances of all bunches at start of store

Store 2441 **Store 2445 ΔQ_y=-0.002**



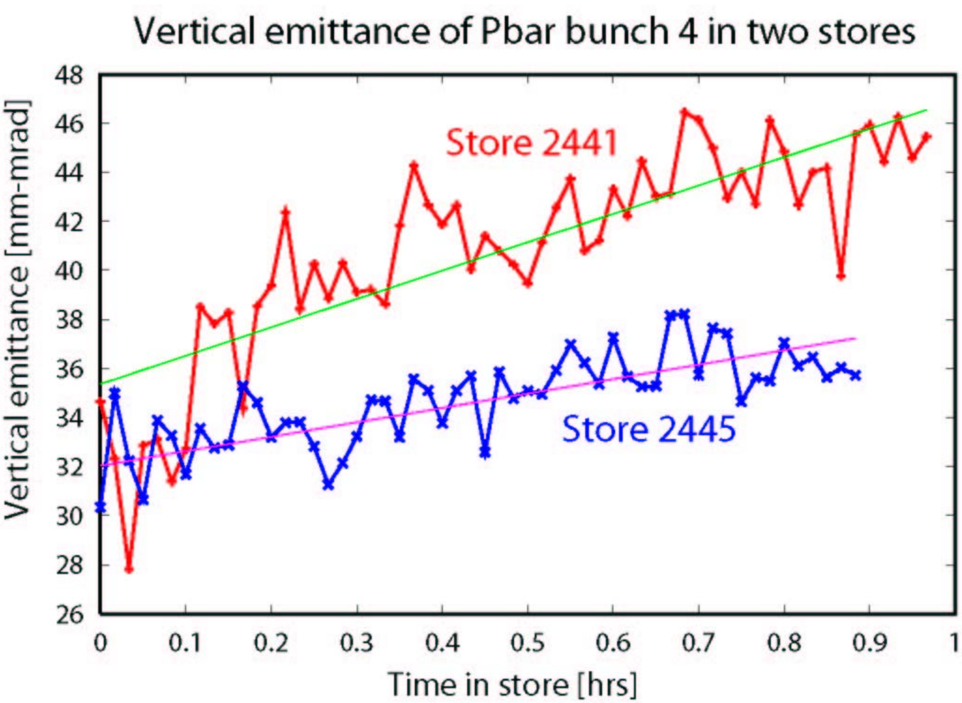


scallop! no scallop



with scallop: emittance growth rates for bunches 1 and 4 are different

synchrotron-light emittances of bunches 1 & 4 during store



emittance growth rate of bunch 4 is different with & w/o scallop

Tevatron (T. Sen)

RHIC – pol.pp, Au-Au, etc.

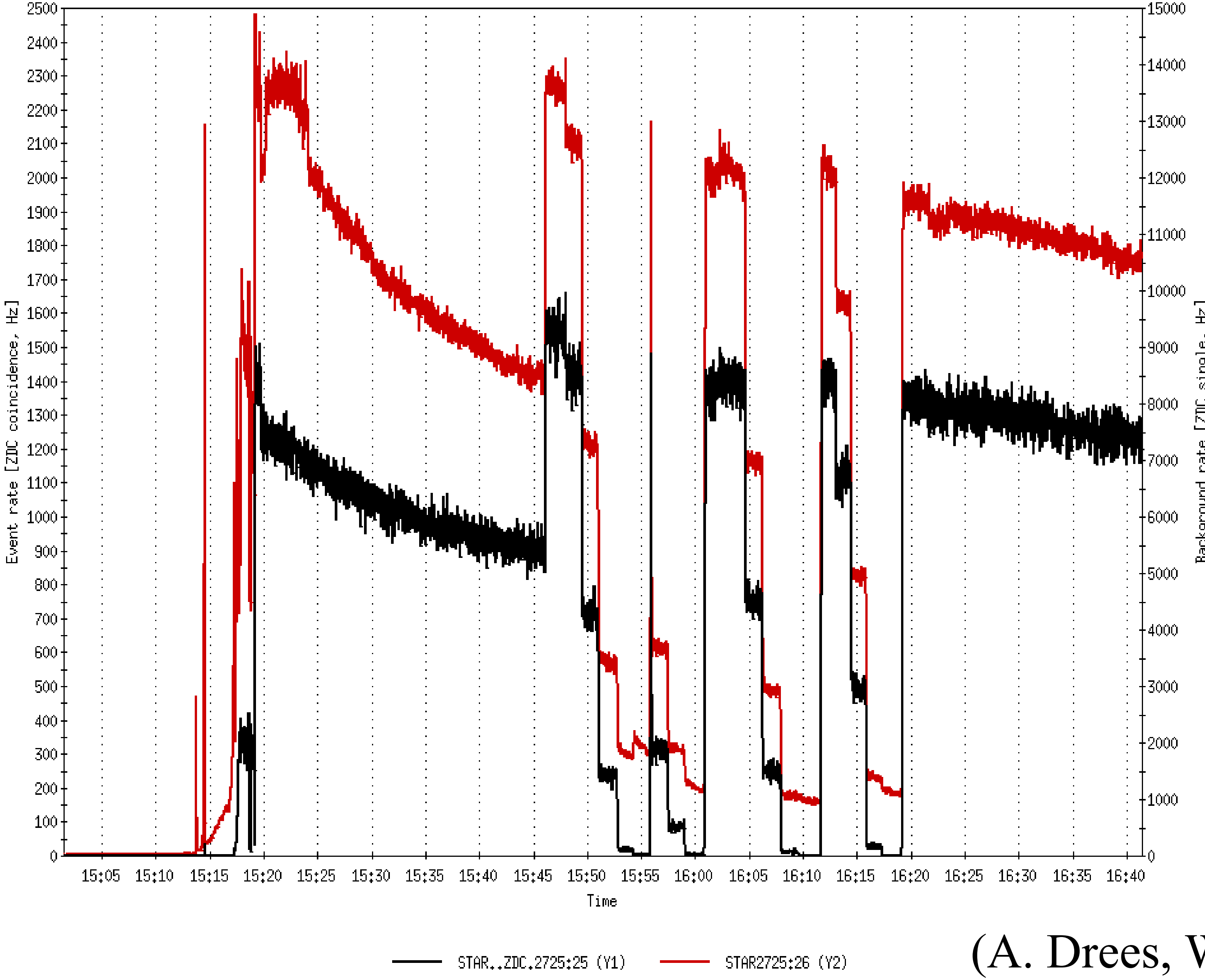
- background is a problem; *due to beam-beam, triplet errors, possibly poor vacuum?*
- even for small beam-beam tune shifts (total - 0.002 in 4 IPs) lifetime is clearly different from without beam-beam
- working point strongly affects beam lifetime and background
- collisions with transverse offset increase background
- amplitude-dependent diffusion rates measured by collimator retraction

(W. Fischer, R. Fliller, and A. Drees)

DAΦNE – low-energy e^+e^- factory

- tail growth is a real problem
- low energy machine; very weak noise and damping
- damping time 110000 turns (compare LEP's 40 turns!)
- in tail simulations resonances up to 12 order & higher are seen, tails due to resonance streaming & diffusion from overlap of synchro-betatron satellites
- measured. lifetime is sensible to tune variation as low as 0 001 due to beam-beam interaction
- no systematic measurements of the tails, but best working points predicted by simulations correspond to better lifetime

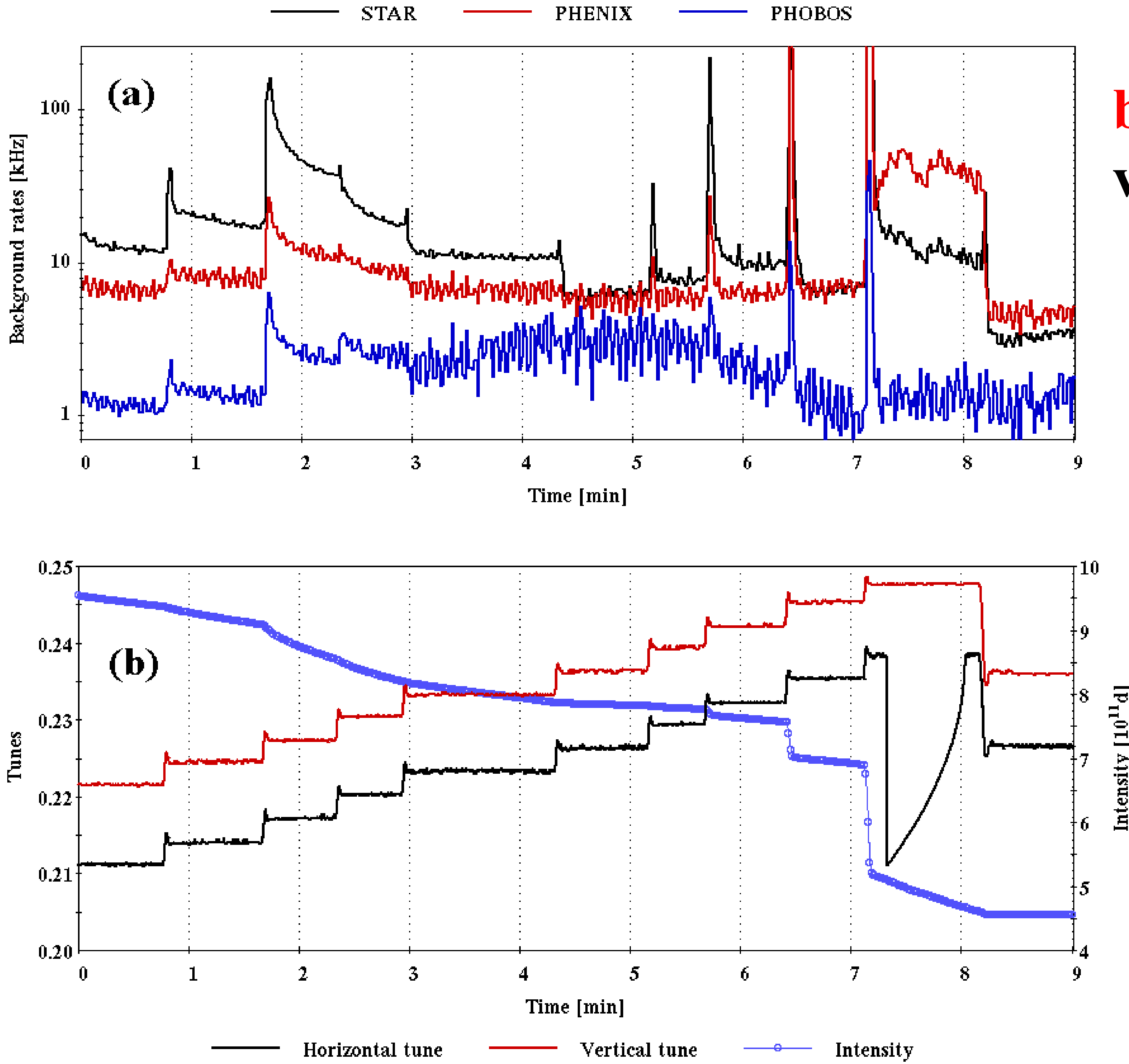
(M. Zobov)



event rate and back-ground with trans-verse offsets (vernier scans)

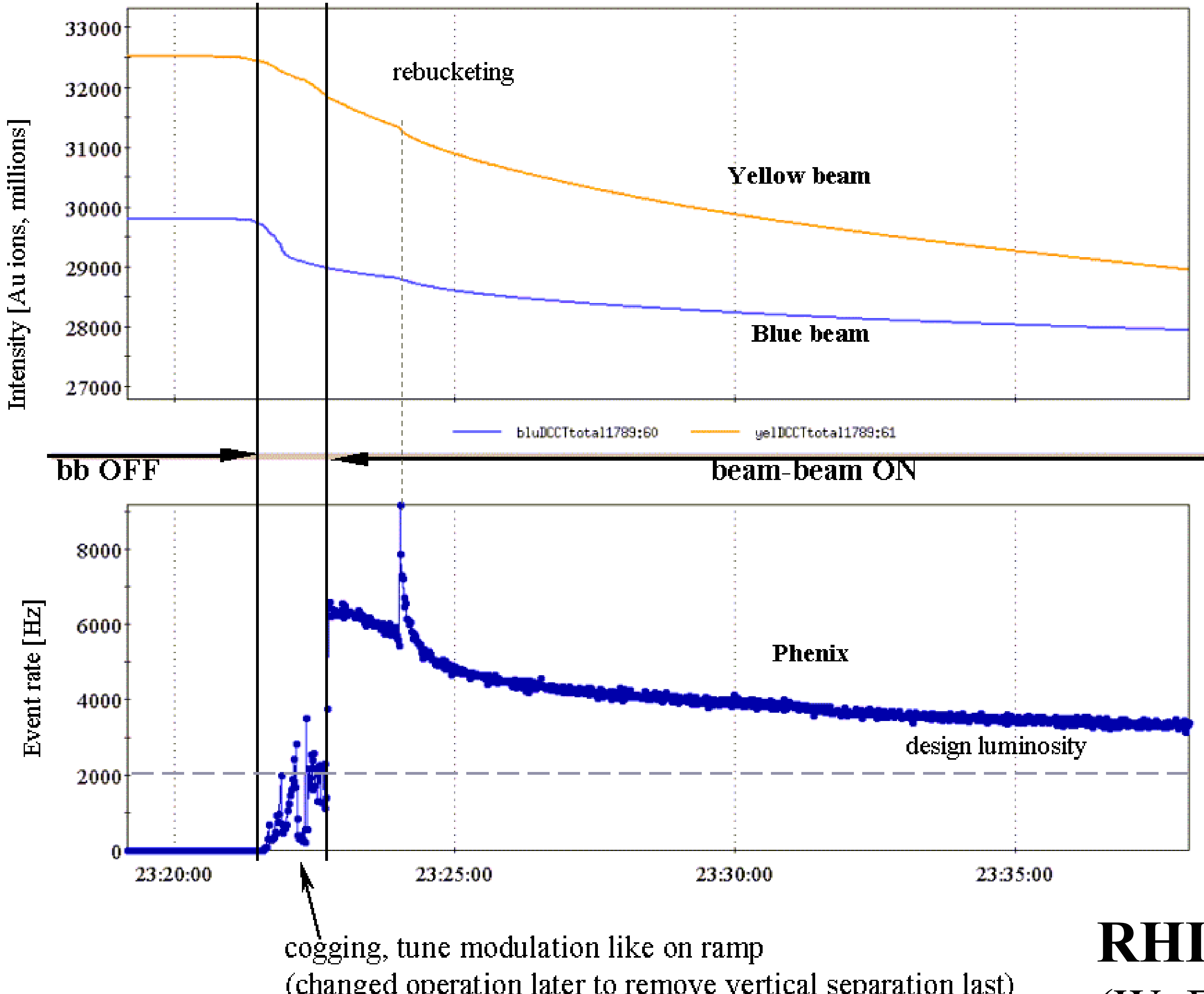
RHIC

(A. Drees, W. Fischer)



background vs tune

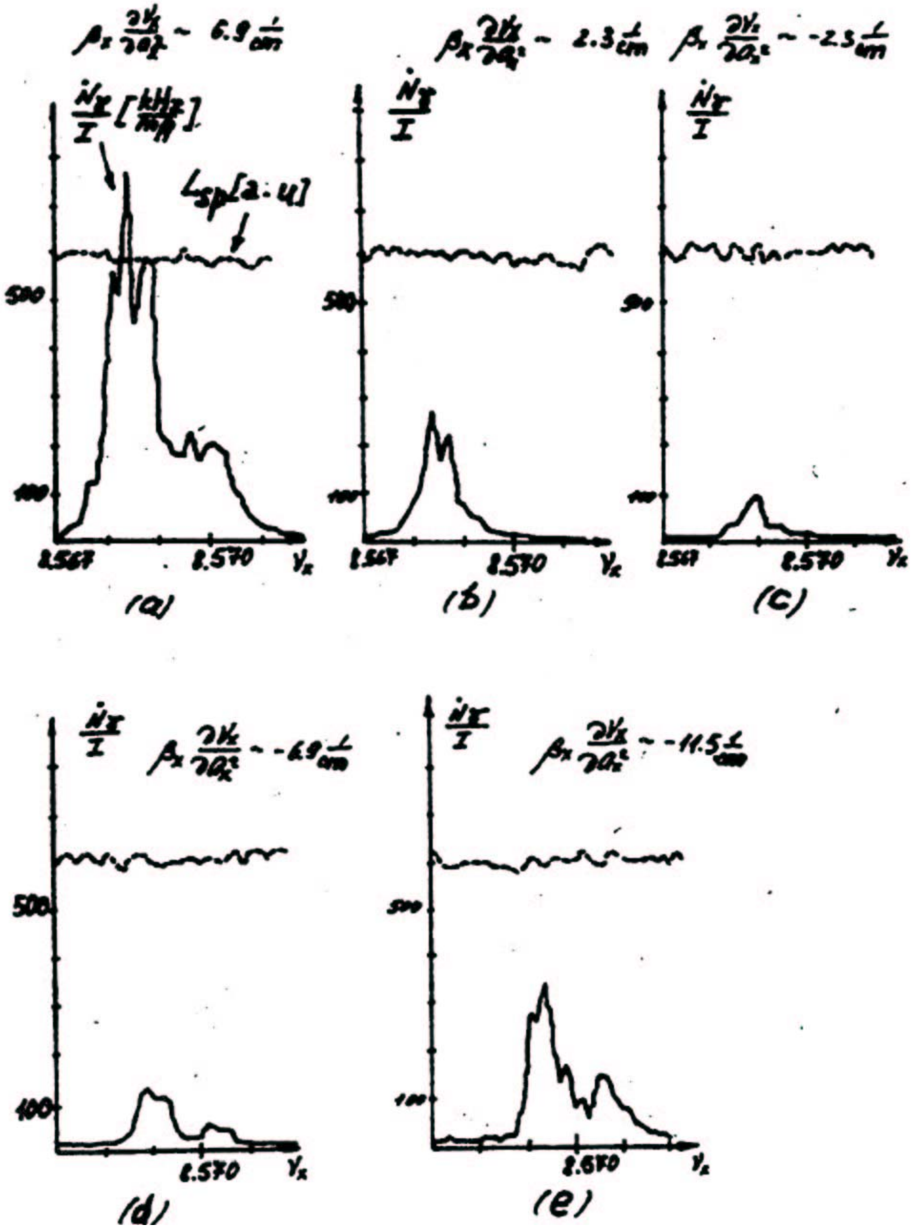
RHIC
(W. Fischer)

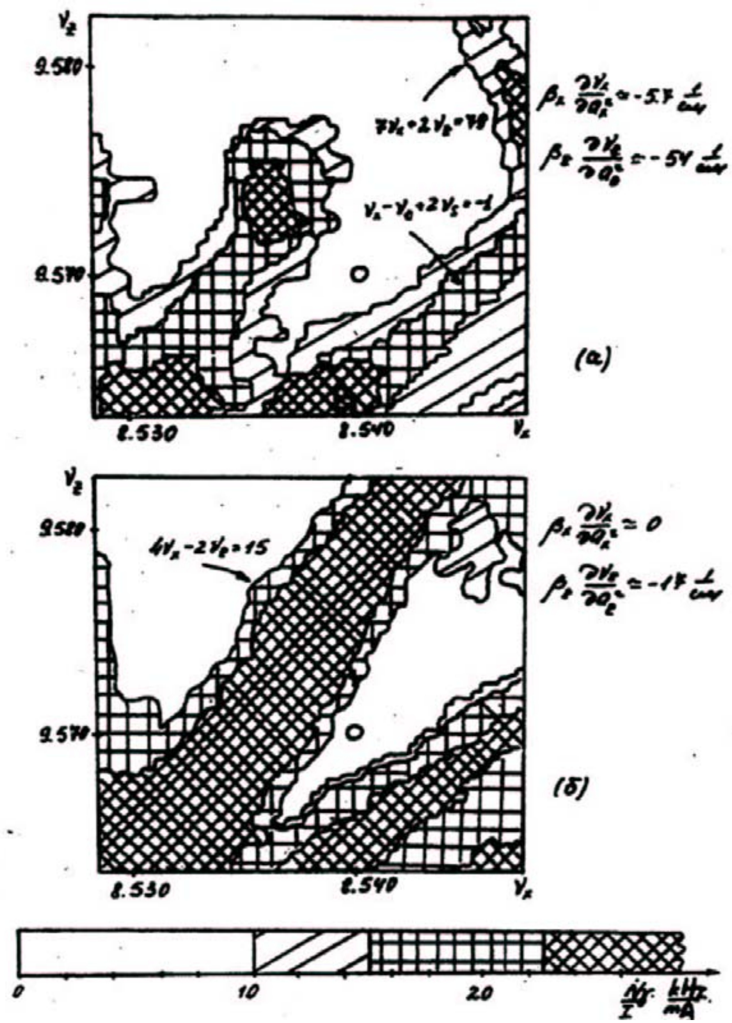


lifetime out of and in collision

RHIC

(W. Fischer)

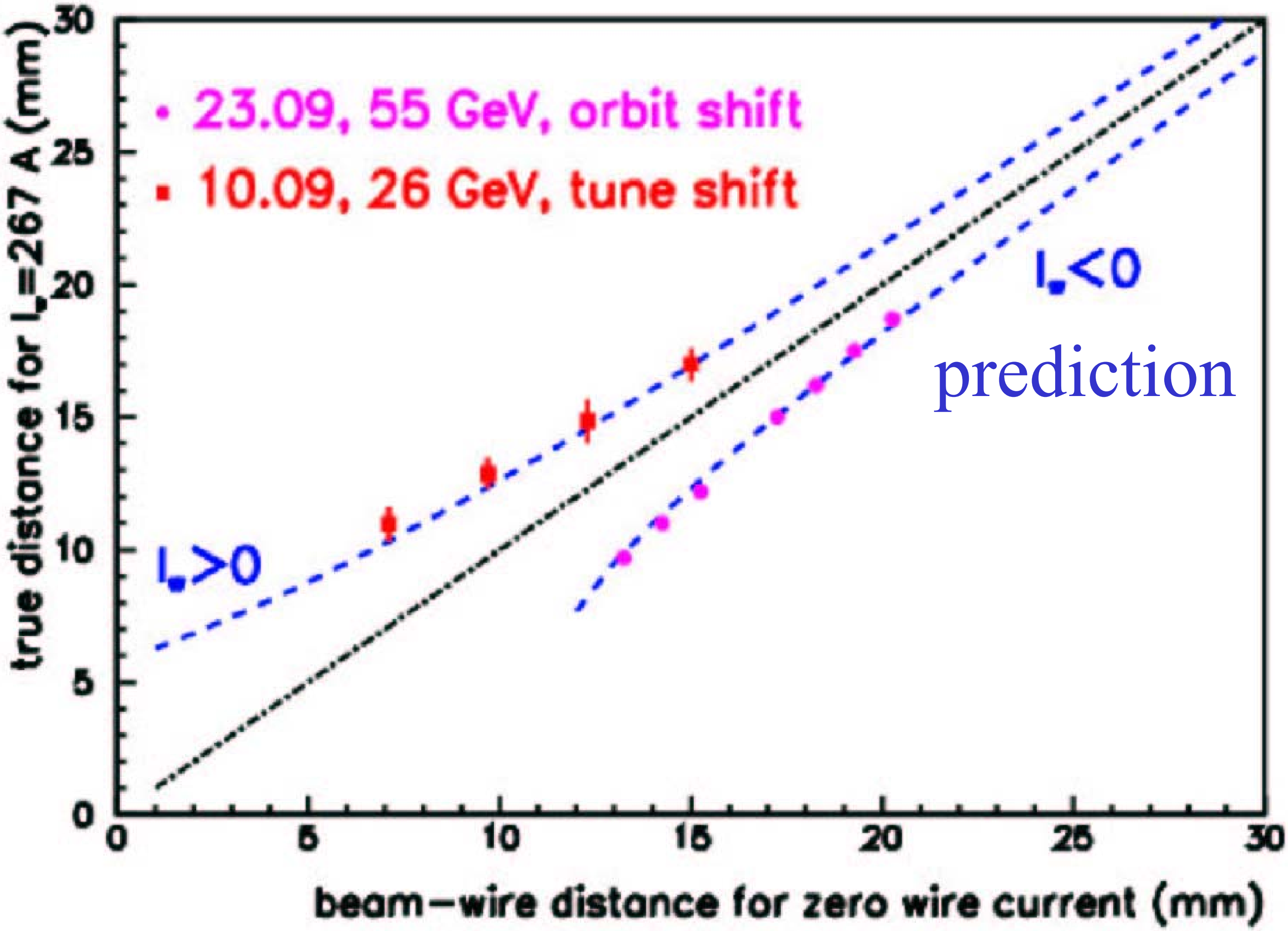

(a)
(b)
(c)
(d)
(e)
500
100
8.567
8.570


9.580
9.570
8.530
8.540
(a)
(б)
0
10
20

Conversion: D –> Δa in Δt

$$\Delta a = \beta\,(\varepsilon_0{}^2\,D\,\Delta t)^{1/2}\,/\,a$$
$$= (\beta\varepsilon_0\,D\,\Delta t)^{1/2}/n_\sigma$$

preliminary result: beam-wire distance derived from tune shift and from orbit change versus prediction:



HERA - the ep collider

- e-p beam-size matching important
- proton emittance grows due to beam-beam
- diffusion measurements

status of SPS study

- tune shift, orbit distortion, beam lifetime, background, emittance reduction were measured; all are consistent with prediction

- we still need to quantify the diffusion rate

- second compensating wire as a next step

- pulsed wire will be technical challenge

1) In simulation, the LRBBC is efficient and robust and opens the way to higher LHC performance.

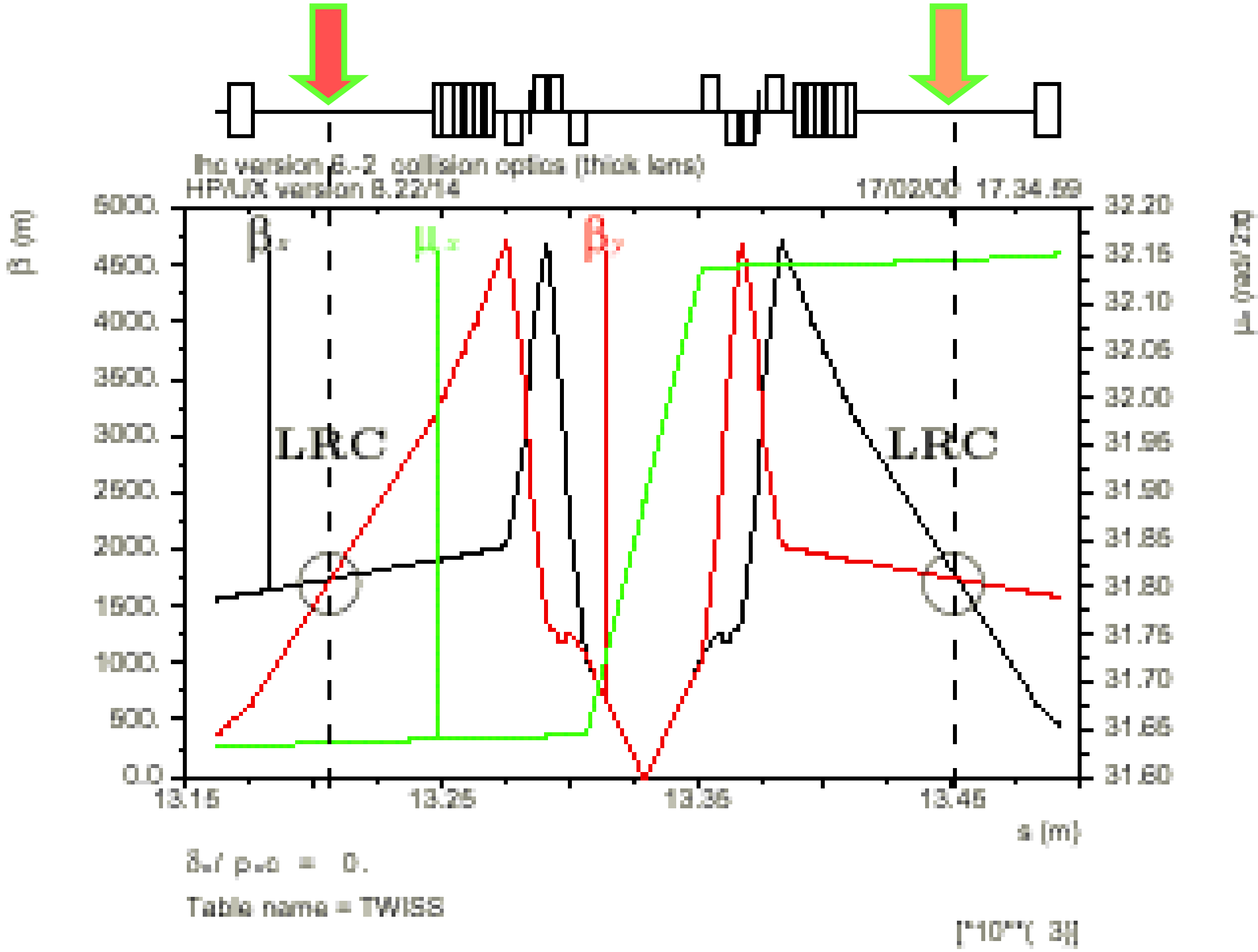
2) It may already be needed to reach nominal performance.

3) It makes the performance independent of the Xing scheme (but is easier to implement for V Xing).

4) A set-up is under test in the SPS (dc mode), with performance beyond LHC requirements (>100A/mm2).

5) The pulsed mode for PACMAN is a technical challenge requiring R&D and doable (G. Schroeder).

Position of the Correctors



Jean-Pierre Koutchouk

Motivation

At the nominal performance level, the long-range beam-beam effect has been recognized to be the limiting mechanism.

The `enlarged' crossing angle (300 μrad, i.e. 9.5σ average separation) and the alternate crossing (cancellation of the linear tune shift) *do not appear to leave a sufficient aperture where the beam motion is well behaved* (Beam-beam workshops CERN 1999, Fermilab 2001).

Proposal made of an active system to cancel the LRBB kicks (LHC Project Note 223 & PAC01 & LHC MAC).